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COMPREHENSIVE SYSTEM-BASED ARCHITECTURE FOR AN INTEGRATED HIGH ENERGY LASER TEST BED

by

HEL Test Bed Team
Cohort 311-133O

March 2015

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COMPREHENSIVE SYSTEM-BASED ARCHITECTURE FOR AN INTEGRATED HIGH ENERGY LASER TEST BED

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LIST OF ACRONYMS AND ABBREVIATIONS

ABL	Air Force on the Airborne Laser
AFIT	Air Force Institute of Technology
AFSB	Afloat Forward Staging Base
AT&L	Acquisition, Technology and Logistics
ATL	Advanced Tactical Laser
BPP	Beam Parameter Product
AoA	Analysis of Alternatives
CAE	Computer Aided-Engineering
CCD	Charge-Coupled Device
CDE	Center for Directed Energy
CONOPS	Concept of Operations
CFA	Controlled Firing Areas
CIWS	Close-In Weapon System
CMOS	Complementary Metal Oxide Semiconductor
CNO	Chief of Naval Operation
DE	Directed Energy
DIMM	Differential Image Motion Monitor
DOD	Department of Defense
EMMI	Energy, Material, Money, and Information
EVM	Earned Value Management
FAA	Federal Aviation Administration
FEL	Free Electron Laser
FMEA	Failure Mode and Effects Analysis
FoS	Family of Systems
FSM	Fast Steering Mirrors
FTE	Full Time Equivalents
GBAD	Ground-Based Air Defense
HEL	High Energy Laser
HELEEOS	High Energy Laser End-to-End Operational Simulation
HELMD	High Energy Laser Mobile Demonstrator

HLA	High-Level Architecture
HSMST	High Speed Maneuvering Surface Target
IPR	Interim Project Reviews
IPT	Integrated Project Team
IRIG	Inter-Range Instrumentation Group
ISR	Intelligence, Surveillance, Reconnaissance
JHP	Joint High Power
JSF	Joint Strike Fighter
JTO	Joint Technology Office
KPP	Key Performance Parameter
LaWS	Laser Weapon System
LCH	Laser Clearinghouse
LEEDR	Laser Environmental Effects Definition and Reference
LIDAR	Light Detection and Ranging
LSDZ	Laser Surface Danger Zone
LSRB	Laser Safety Review Board
M&S	Modeling and Simulation
MIRCAL	Mid-Infrared Advanced Chemical Laser
MLD	Maritime Laser Demonstrator
MOA	Military Operations Area
MOE	Measure of Effectiveness
MOP	Measure of Performance
MPE	Maximum Permissible Exposure
MSSE	Masters of Science in Systems Engineering
MTBF	Mean Time Between Failures
MRTFB	Major Range and Test Facility Base
NAVSEA	Naval Sea Systems Command
NAWS	Naval Air Weapons Station
NBVC	Naval Base Ventura County
NOAA	National Oceanic and Atmospheric Administration
NOHD	Nominal Ocular Hazard Distance

NOMADS	National Oceanic and Atmospheric Administration Operational Model Archive Distribution System
NOMAR	Notice to Mariners
NOTAM	Notice to Airmen
NPS	Naval Postgraduate School
NSWC	Naval Surface Warfare Center
NSWC DD	Naval Surface Warfare Center Dahlgren Division
NSWC PHD	Naval Surface Warfare Center Port Hueneme Division
ONR	Office of Naval Research
PMP	Project Management Plan
PPE	Personal Protective Equipment
QRC	Quick Reaction Capability
R&D	Research and Development
RDT&E	Research Development Test & Evaluation
ROM	Rough Order of Magnitude
SE	System Engineering
SME	Subject Matter Expert
SOP	Standard Operating Procedure
SPAWAR	Space and Naval Warfare Systems Command- SSC Pacific
SSL	Solid State Lasers
SUA	Special Use Airspace
TDA	Technical Direction Agent
THEL	Tactical High-Energy Laser
TLS	Tactical Laser System
TM	Tech Maturation
TSPI	Time-Space-Position Information
UAS	Unmanned Aerial Systems
UAV	Unmanned Aerial Vehicle
US	United States
USD	Under Secretary of Defense
USMC	United States Marine Corps
VV&A	Verification, Validation, & Accreditation

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EXECUTIVE SUMMARY

Over the past several decades, High Energy Laser (HEL) technology has seen great progress. Laser technology has greatly matured, and though large gas and chemical lasers are still the most powerful, recent advances have made smaller and portable Solid State Lasers (SSL) viable weapons. As a result, the U.S. Navy has shown increased interest in HEL systems for use in the maritime environment. As a matter of fact, the Office of Naval Research (ONR) is currently pursuing the "development and demonstration of an advanced, ship-based High Energy Solid State Laser (SSL) weapon system prototype to address Surface Navy capability gaps for area and close-in self-defense and Combat Identification/C4ISR" (ONR 2012).

Although several test events have occurred on land test ranges, the results yielded in these cases do not directly apply to the environment in which the Navy operates. Moreover, test events have taken place at various test ranges to attempt to determine the effectiveness of laser weapons in a marine environment. Still, there is no one single test range that provides the Directed Energy (DE) community with a test environment that is complete with an over-ocean propagation range, sensors and instrumentation, and modeling and simulation support to ensure that laser weapon systems can be fully tested and integrated prior to deployment.

This capstone investigates the requirements for developing an all-encompassing HEL test bed that will provide the Navy with the means to accomplish all required testing for proposed DE weapons. More specifically, the mission of this study is as follows:

Develop a conceptual architecture and a set of requirements for testing and evaluating HEL weapon systems and atmospheric characterization tools in a maritime environment. Identify the technologies, both existing and under development, capable of supporting HEL testing. Identify resources that will support HEL testing on a range including the integration of these assets.

As stated above, the objective of this study is not to identify an existing range that can be used to meet all testing requirements; rather, this study focuses on developing the

architecture to create (or select) a test range that will satisfactorily meet all HEL testing requirements. The analysis suggests that the centralized test bed would be the recommended solution for implementing a HEL test bed for the Navy. The overall effectiveness of each variant was assessed and validated against the architecture developed.

A systems approach was taken to arrive at this conclusion, which started with the development of specific requirements. HEL testing stakeholder needs were discussed in order to develop a comprehensive list of testing requirements that must be met. These stakeholder-derived requirements were then translated into capabilities that the test bed must have. A Model Based System Engineering approach was used to develop physical, functional, and allocated models of the HEL test bed and all its components. An analysis of alternatives was then performed among multiple test bed variants to determine how well each variant accomplished the desires of the stakeholders from a cost, schedule, and performance perspective.

Finally, a systems integration plan was developed to successfully combine subsystems and components involved to ensure that their synthesis adequately met the system’s high-level requirement and function. The essential elements for developing a fully capable HEL test bed have been identified in this study. Potential future research would be a comprehensive range study to clearly identify the ranges capable of supporting this mission for the Navy. Also, a more in-depth cost analysis would be warranted to provide additional resolution into the cost and comparison between alternatives.

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I. INTRODUCTION

Harnessing the power of light has captivated the human mind for centuries. In 212 B.C., Greek commander Hippocrates is said to have employed the Archimedes giant concave mirror to focus the sun's rays to set fire to the sails of attacking Roman ships. In science fiction, lasers were the ultimate weapons: The Martian "heat ray" from *The War of the Worlds*, the "phasers" from *Star Trek*, and the planet destroying power of the "Death Star" from *Star Wars* are just a few examples of their awe-inspiring power depicted by the media.

However, no longer are lasers purely the realm of science fiction. High Energy Laser (HEL) and Directed Energy (DE) weapons are currently in development by all U.S. services. The past 40 years has seen the progression from large gas and chemical lasers to Free Electron Lasers (FEL) and smaller, powerful, and more portable Solid State Lasers (SSL). Though chemical lasers are still the most powerful, recent advances have made SSL a viable weapon.

In December 2013, the Army successfully completed testing of the High Energy Laser Mobile Demonstrator (HELMD) at White Sands Missile Range in New Mexico. HELMD destroyed up to 90 mortar rounds and several aerial drones utilizing a truck mounted 10 kW laser. Eventually, incoming cruise missiles, rockets, and artillery shells will meet a similar fate (Thomson 2013).

The United States Marine Corps (USMC) announced on 11 June 2014 that it have finished awarding contracts for their Ground-Based Air Defense Directed Energy On-the-Move program, commonly referred to as GBAD. GBAD seeks to utilize a laser system on light tactical vehicles like Humvees to protect Marine units from enemy Unmanned Aerial Vehicles (UAVs). Some of the system components have already been used to successfully detect and track UAVs of various sizes. System tests were planned for late 2014 involving a 10 kW laser to be used as a stepping stone to 30 kW lasers (Beidel 2014).

Much of the research for GBAD is being performed at Naval Surface Warfare Center (NSWC) Dahlgren, which highlights the importance the Navy is placing on DE.

Indeed, the Chief of Naval Operation (CNO) recently placed additional emphasis on DE and expanding the range of its capabilities. DE weapons are seen as the future for defending ships at sea as well as our soldiers on the ground and in the air.

To underline the importance the Navy is placing on the development of HEL weapon systems, the Office of Naval Research (ONR) is currently pursuing the "development and demonstration of an advanced, ship-based High Energy Solid State Lasers (SSL) weapon system prototype to address Surface Navy capability gaps for area and close-in self-defense and Combat Identification/C4ISR" (ONR 2012). ONR plans to assess the technical maturity of solid state lasers and the feasibility of integrating a laser weapon onto a Navy surface combatant.

According to a report conducted in 2014 by Ronald O'Rourke of the Congressional Research Service,

> Lasers are of interest to the Navy and other observers as potential shipboard weapons because they have certain potential advantages for countering some types of surface, air, and ballistic missile targets. Shipboard lasers also have potential limitations for countering such targets.

HEL weapon systems under development for the Navy have a specific set of targets within the categories listed above. Specifically, UAVs and small boats are of particular interest to the Navy due to the potential information gained or damage caused by these platforms. Highlighted by the attack on the USS Cole in 2000, these platforms are capable of carrying ordinance that can severely harm U.S. surface combatants operating in littoral waters. Considering these threats are relatively inexpensive, there is also significant interest due to the dramatic cost difference of firing a low-cost per shot HEL compared to a multi-million dollar missile.

In the summer of 2014, USS Ponce deployed to the Persian Gulf as an interim Afloat Forward Staging Base (AFSB), armed with the Laser Weapon System (LaWS). LaWS has been upgraded as part of the Quick Reaction Capability (QRC) Program led by ONR. LaWS utilizes a Close-In Weapon System (CIWS) mount to provide target acquisition data to the HEL weapon tracking system. This effort will allow for continued evaluation of shipboard lasers in an operational environment and may aid in mitigating risks, for future systems, associated with fielding a laser weapon at sea.

Ballistic missiles also fall into the category of threats that HEL weapon systems seek to combat; however, there are some challenges with the laser's ability to destroy ballistic missiles. One of the major challenges is the achievable power levels produced by current SSL systems is not enough to defeat the hardened exteriors of these weapons. Nevertheless, it will not be long before SSL weapons reach multiple hundred kW levels. With the Navy standing at the forefront of SSL technology and HEL weapon system development, there is understandably a need within the agency to provide a clear path to effectively and efficiently test and evaluate these systems within current fiscal constraints.

Laser test ranges are designed primarily with safety in mind. Since 1979, the Naval Surface Warfare Center (NSWC) Dahlgren has served as the Navy's Technical Direction Agent (TDA) for laser safety by conducting safety surveys of ranges and providing technical assistance and guidance in the safe use of laser systems (Ramsburg, Jenkins, and Doerflein 1982). Isolated areas of desert or water are set aside to limit human interference. Not to imply that safety is unimportant, it is simply one of many factors required in the development and utilization of a range. Often the ranges were designed for other weapons systems and adapted for use by HELs.

In the past, there have been a number of tests and experiments conducted at various test ranges to determine the effectiveness of laser weapons in a marine environment. There are no locations that provide the DE community with a test environment that is complete with an over ocean propagation range, sensors and instrumentation, and modeling and simulation support to ensure that laser weapon systems can be fully tested and integrated prior to deployment. A test bed with these attributes would not only allow for systems to be tested, but would create a method for gathering data to validate atmospheric and systems effectiveness models. As laser weapon system development continues to ramp up, an asset of this type is necessary to provide the Navy with a capability to support the test and evaluation of laser weapon systems and sensors that require influence from a marine environment.

A systems-based approach was utilized for the development of the Navy's HEL test bed architecture. This involved looking at the system, in this case a HEL test bed, in its entirety: components, inputs, outputs, controls and constraints, and their interactions with each other and with external entities. The process started with requirements development, which involved discussions with stakeholders, beginning with a formal meeting and continuing throughout the project. Needs and stakeholder analysis enabled the development of a formal requirements list for the test bed.

The next phase involved the translation of the requirements into capabilities of the test bed. An architecture for the test bed was developed using CORE and an Analysis of Alternatives (AoA) was performed to determine the most effective implementation of the test bed. This utilized a set of evaluation criteria derived from the requirements and incorporated relative cost and risk of the alternatives. The results and recommendations are documented in this report.

A. BACKGROUND

The Navy was in the forefront of early HEL development. It created the world's first megawatt-class, continuous-wave, Mid-Infrared Advanced Chemical Laser (MIRCAL) located at White Sands Missile Range (WSMR). MIRACL was used to successfully engage static and aerial targets. This spawned work by the Air Force on the Airborne Laser (ABL) and the Army with the Tactical High-Energy Laser (THEL). In 2000 and 2001, the THEL shot down 28 supersonic artillery rockets and five artillery shells. In 2010, the ABL successfully engaged and destroyed tactical ballistic missiles during the boost phase of flight. All of these systems were large chemical lasers. These systems utilized toxic chemicals to generate their lasing action and had a large footprint. With the exception of ABL which was extremely expensive to develop, these systems were not portable. Even if they were designed to be mobile, as was THEL, the risk of deploying these weapons in theater was too risky given their toxic makeup and potential use in high sea-states.

In recent years, SSL have moved to the forefront of Research and Development (R&D). The Navy is keen on developing lasers for shipboard self-defense, force protection, and both air-to-ground and air-to-air engagements. In 2004, Naval Sea Systems Command (NAVSEA) designated the Directed Energy Weapons Program Office (PMS 405) as the point of contact for DE and electric weapons systems development. Their primary goal is to transition technology from the laboratory to prototype/advanced development/testing for operational development and use. A brief survey of recent HELs in testing includes the previously mentioned LaWS, the Mk 38 Tactical Laser System (TLS), and the Maritime Laser Demonstrator (MLD).

LaWS, is an application of fiber SSL that are widely used in industry for cutting and welding metal (Figure 1). It utilizes six welding lasers that are incoherently combined into a 33kW beam with the capability to disable or destroy targets. The system successfully shot down five UAV targets in five attempts at Naval Air Weapons Station (NAWS), China Lake in 2009. In 2010, it utilized a Close-In Weapon System (CIWS) as a target acquisition source to shoot down four UAVs in four attempts at a range of about one nautical mile in an over-the-water setting at San Nicholas Island, CA. Between July and September 2012, LaWS successfully engaged three UAVs in three attempts onboard Arleigh Burke class destroyer USS Dewey off the coast of San Diego, CA. LaWS began an operational deployment to the Persian Gulf, aboard the USS Ponce, in the summer of 2014 (O'Rourke 2014).

Figure 1. Laser Weapon System (LaWS)

Mk 38 TLS is another fiber SSL with a beam power of 10 kW (Figure 2). It is employed on an Avenger mount alongside the Mk 38 25mm machine gun that is mounted on many surface combatants. Testing has been performed primarily at Eglin Air Force Base from shore-to-sea at small boat targets. Other tests have also taken place in 2012 at Dahlgren (Mitchel 2011).

Figure 2. Mk 38 Tactical Laser System (TLS)

MLD is a joint Army/Navy venture with Northrop Grumman which leveraged development work on slab SSL done elsewhere in the DOD under the Joint High Power SSL (JHPSSL) program (Figure 3). In March 2009, Northrop demonstrated a version of MLD that coherently combined seven slab SSLs to create a beam power of about 105 kW. In July 2010, it completed a tracking demonstration at NSWC Port Hueneme, followed by a lethality demonstration at NSWC Dahlgren against stationary small boats the following August and September. In 2011, it conducted successful open-ocean testing onboard a decommissioned Spruance-class destroyer, the ex-USS Paul F. Foster (EDD 964) (Figure 4) (Thompson 2013).

Figure 3. Maritime Laser Demonstrator (MLD)

Figure 4. Ex-USS Paul F. Foster (EDD 964) (from Willshaw, Fred 2015)

This was the first time that a laser of this energy level had been put on a Navy ship, powered from the ship and used to engage a target at range in a maritime environment.

In the current fiscal environment, sequestration is a reality, and a government shutdown is hardly a distant memory. ONR funding identifies approximately $110 million from FY13-FY16 for the development of DE weapons (ONR 2012). By comparison, the

F-35 Joint Strike Fighter (JSF) program was funded at $5.1 billion for FY14 alone (Gertler 2014). The $110 million includes not only the research and development of DE prototypes, but also includes all inherent government responsibilities for the test and evaluation of afloat and ashore platforms. With relatively limited funding available and to curtail future sequestrations and shutdowns, a systems-based approach to testing would provide a far more cost effective means to conduct HEL testing and DE Research Development Test & Evaluation (RDT&E).

B. PROBLEM STATEMENT AND PROJECT OBJECTIVES

High Energy Laser (HEL) weapon development is reemerging as a main focus within the Department of Defense (DOD) and has become one of the Navy's top priorities. The three most recent laser weapon systems discussed (Chapter I, Section A), were developed in different locations and tested at five different ranges across the nation. These tests were particularly significant for the maritime community given three of the ranges involved over water testing. In order to perform these tests, agencies and companies involved in HEL testing were required to transport their gear, operators, and engineers to the selected test ranges. Each test required much of the same equipment from the previous HEL weapon system test. Since no single activity controls or manages all of the equipment, support must be brought in for each event. The ability to adequately test HEL weapons and laser related systems is limited to a few test ranges due to the necessity for a maritime environment, particular range capabilities, and various other geographical and atmospheric characteristics.

The problem that the Navy will face as HEL Weapons evolve is:

The U.S. Navy is lacking an integrated, cost-effective method or system for testing HEL weapons in a maritime environment.

In an effort to facilitate the development of a HEL test bed(s) in the future, the objective of this study is to:

Develop a conceptual architecture and a set of requirements for testing and evaluating HEL weapon systems and atmospheric characterization tools in a maritime *environment. Identify the technologies, both existing and under development, capable of supporting HEL testing. Identify resources that will support HEL testing on a range including the integration of these assets.*

Lastly, whether the Navy decides that a single location or multiple locations should be selected to be the laser test range, this thesis will provide an architecture for developing the capabilities necessary to support developmental HEL and atmospheric characterization testing.

C. RESEARCH QUESTIONS

The preliminary investigation into this topic posed multiple questions about the planning for future Navy testing of high energy lasers. This could be partly due to the rapid emergence of solid state laser technology and its viability as a Naval weapon in the near future. The questions listed below are the foundation of this thesis on Navy testing of high energy lasers and the implementation of a Navy HEL test bed.

- How are the physical and functional elements that comprise the architecture of a U.S. Navy HEL test bed related? How are the elements integrated, and what is the role of each element as it relates to the established requirements?
- Which of the following HEL test bed architectural concepts can best meet the needs of the Navy: centralized, multiple equipped ranges, or fly-away team? What are the deciding factors that make this the best option? How were the attributes weighted?
- What are some of the inherent range attributes required so that the HEL test bed can successfully meet all requirements for each test scenario?

D. ASSUMPTIONS AND CONSTRAINTS

This section describes both challenges discovered while developing this thesis and the assumptions and constraints used to guide this research. The most significant constraint for completing this thesis was time. The total project timeline is a mere nine months long from conception to completion. The project was conducted via video conferencing due to distributed team member location and frequent work related travel. Another major constraint was the challenge of managing distribution sensitive material while utilizing non

Navy collaboration tools. To mitigate this issue, this report was written containing open source material only.

Some of the key assumptions made throughout the development of this thesis pertained to the capabilities of potential ranges, types of HEL technologies in question and types of Navy tests. In particular, the goal of this study is not to identify a test range that should be designated for all HEL system testing in the future. It is assumed that the range selected to support HEL testing for the Navy will provide certain inherent capabilities (i.e., range radars, shore power, test sites) which will not be thoroughly discussed as part of this thesis.

It is assumed that the test bed will be able to support various HEL technologies, but recent developments suggest the test bed will first support solid state and fiber lasers. The thesis was developed with the assumption that the test bed would support DT&E of HELs on surface craft, airborne platforms, and shore sites.

Some anticipated constraints and controls for conducting HEL operations on the test bed are weather, range availability, and range safety. The Laser Safety Review Board (LSRB) will not necessarily act as a constraint for the test bed, but LSRB approval will be required for most laser systems being tested on the range. The same applies to the Laser Clearing House (LCH), as it does not necessarily constrain testing. Coordination with the LCH will be required to ensure space systems are not affected by laser operations. Also, predictive avoidance systems that are integrated into laser weapons will dictate when the weapon is safe to fire.

E. SYSTEM ENGINEERING PROCESS

The System Engineering (SE) staircase model, Figure 5, was used as a framework to generate a Comprehensive Systems Based Architecture for an Integrated High Energy Laser (HEL) test bed to satisfy the mission described above. The development process began at the top of the staircase and progressed down one step at a time. To aid in traceability back to the requirements, feedback from a particular step climbs up one level to ensure alignment with the previous step. The methodology served as a type of checks and balances to verify that steps immediately above and below are in agreement with the objectives, scope, assumptions, and constraints of the current step. In this fashion, ultimately all steps are guided towards a common and structured direction to fulfill the shared goal.

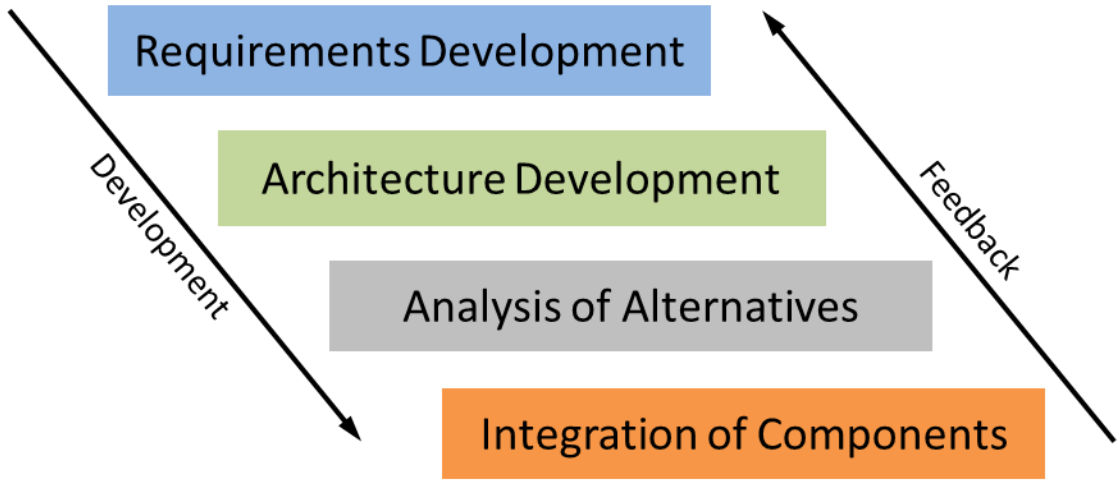


Figure 5. Tailored SE Process

The elements and subsystems of the architecture and their interactions were identified and arranged as functional entities to realize a test bed that would meet the requirements to adequately assess HEL systems.

In order to reduce the complexity and ambiguity in creating such as system, a general SE process described as follows was used to manage its development and integrate its components into the architecture to successfully meet the desires of the stakeholders. The general SE process applied is given via four major categories: requirements development, architecture development, analysis of alternatives, and integration of components (Figure 6). The categories were performed by way of bidirectional arrows as shown to ensure traceability back to the requirements.

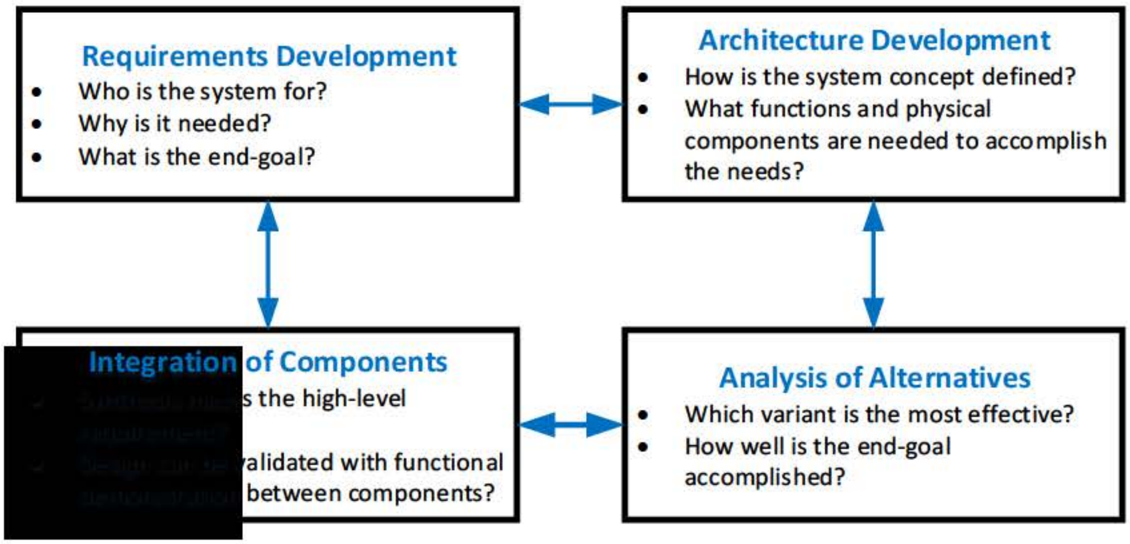


Figure 6. General SE Process Applied

During requirements development, a needs analysis was first conducted via communication with stakeholders to attain a greater understanding of why the system was needed and what functions the system was to perform. High-level requirements were identified, decomposed, and translated into functions that the system was to accomplish. In doing so, the development of the architecture was initiated with the realization of a functional model of the system using DODAF v1.5 Volume II as guidance. The DODAF v1.5 Architectural Development Process is a six step process that guided the architecture development by providing an overarching framework, Figure 7.

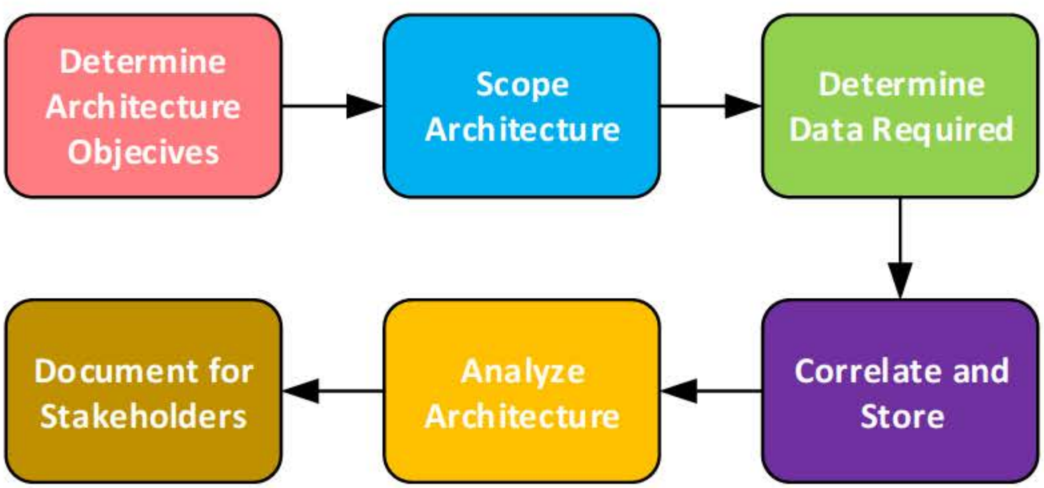


Figure 7. DODAF 1.5 Architectural Development Process

A physical model was then generated to determine the physical elements necessary to carry out the identified functions. Architecture development concluded with the creation of an allocated model which mapped the physical components to the functions identified. This architecture defines the system concept and describes how the end product will accomplish the mission.

An analysis of alternatives was then performed among multiple test bed variants to determine how well each variant accomplished the desires of the stakeholders from a cost, schedule, and performance perspective. The overall effectiveness of each variant was assessed and validated against the architecture developed. Consequently, an alternative was identified that minimized the resources of the U.S. Navy while still meeting the objectives of the system.

Finally, system integration was performed to assimilate the subsystems and components involved to ensure that their synthesis adequately met the system's high-level requirements. Figure 8 shows the tailored processes' five steps that were followed to develop the integration plan for the HEL test bed, which stems from (Langford 2012, 120–123). This is an iterative process that required some steps be performed more than once.

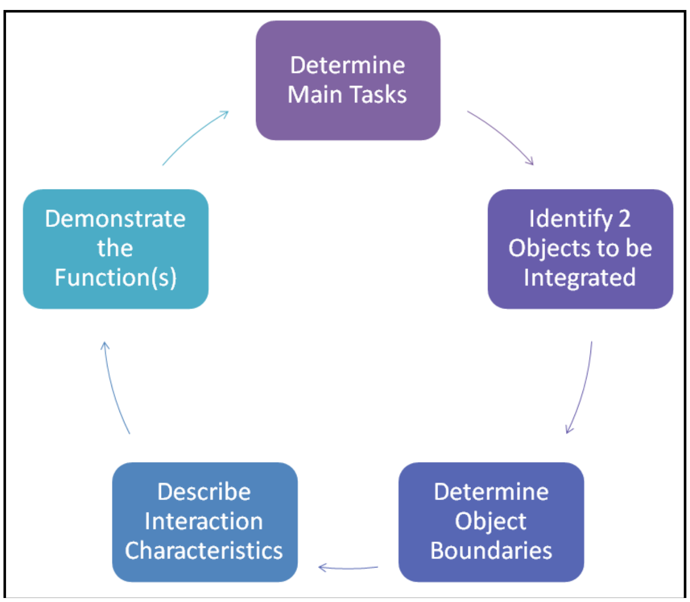


Figure 8. Integration Plan Development Steps

II. REQUIREMENTS ANALYSIS AND CONCEPTUAL DESIGN

The tailored SE staircase model began with preliminary research prior to requirements development (Figure 9). Meeting with the stakeholders provided insight into the current issues and desired capabilities for HEL weapon system testing. High-level requirements and context diagram were developed from these initial meetings and were reviewed with the stakeholders. After stakeholder concurrence of the high-level requirements and context diagram, the functional requirements were developed. The same process of integrating feedback from the stakeholders was employed in the development of the OV-1 and test scenarios (Figure 10).

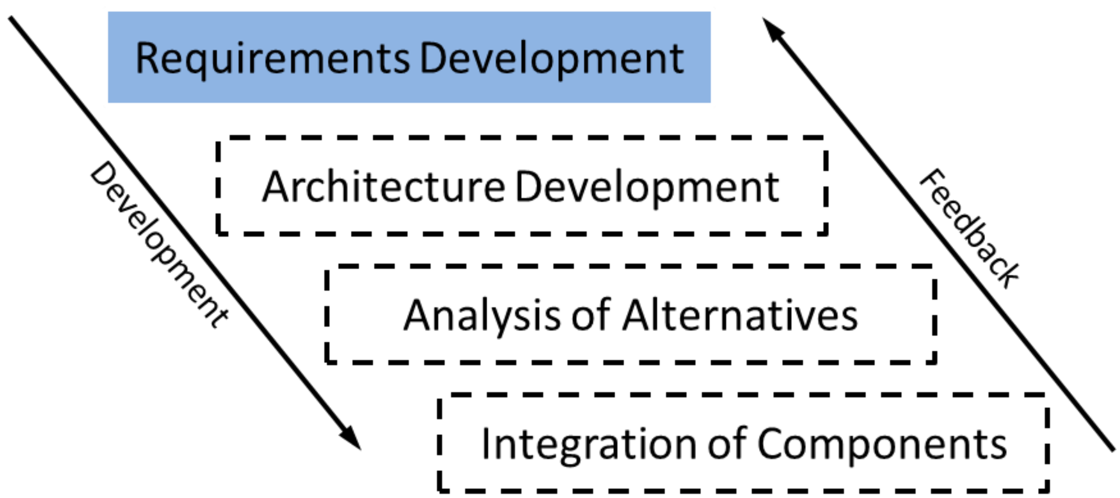


Figure 9. Tailored SE Process: Requirement Development Stage

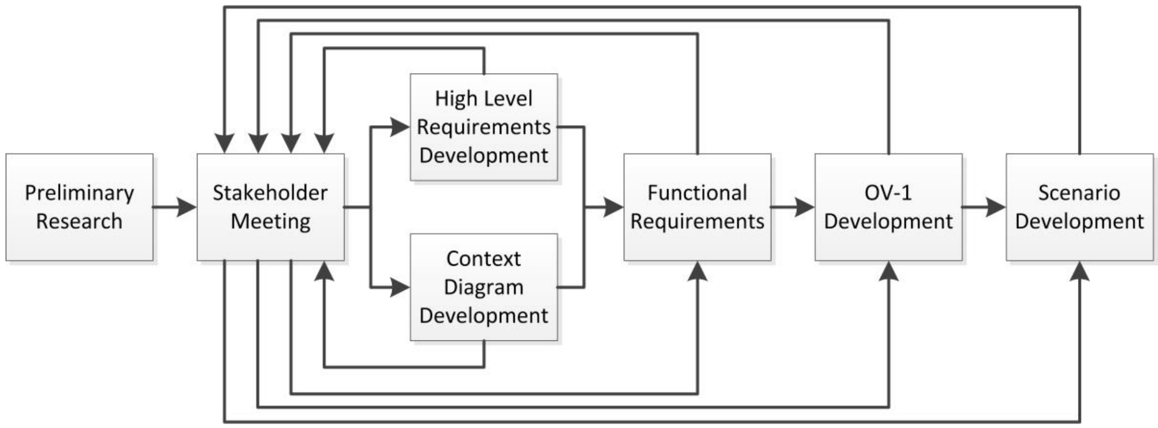


Figure 10. HEL Test Bed Process Development

HEL testing performed at various locations throughout the nation has shown a possibility for a wide range of laser applications for defense. HEL systems have the potential to provide close-in protection when faced with approaching small surface vessels, for instance. Under favorable conditions, HEL systems can also provide protection from high altitude enemies that pose a surveillance and reconnaissance threat. Technological advancements in laser beam generation have also created favorable form factors for DE systems that are more easily transported and powered, such as solid state laser systems.

As the availability of DE systems increases, the need for the capability to test developing systems has similarly increased. To address this testing shortfall, needs from the DE community were gathered to build a comprehensive list of testing requirements for assessing HEL weapons systems and atmospheric characterization tools. The stakeholders involved with the requirements development and the high-level needs outlined during initial meetings are listed in Table 1 and Table 2, respectively. The testing requirements largely stemmed from the need to analyze performance and effectiveness data for the system under test.

Due to the multitude of factors involved in calculating the effectiveness of any HEL weapon system, the need for a variety of test scenarios may arise in order to thoroughly capture the capabilities and limitations of the system under test. A high-level operational concept graphic was developed to depict the available engagement scenarios required from a maritime DE test bed, with the corresponding concept of operations section (Chapter II, Section D) depicting the details of each scenario. Each of these engagements presents its own challenges upon which the maritime environment places additional limitations that were taken into consideration. The overarching range requirements necessary to run the DE system test scenarios in a maritime environment are outlined in section E.

A. STAKEHOLDERS

Due to the increasing demand for laser testing capabilities, the DE community and additional stakeholders listed in Table 1 expressed interest in the development of a HEL test bed. In an effort to characterize the necessary elements of a directed energy test bed, input from the stakeholders was consolidated into a set of high-level needs.

Table 1. Stakeholders

Stakeholder	Category	Description
Directed Energy (DE) Community	Passive	DE community (government and contractor entities) is interested in testing in a maritime environment.
SPAWAR-Atmospherics Branch	Active	Interested in Atmospheric effects testing for High Energy Laser propagation along with atmospheric prediction model validation.
Office of Naval Research (ONR)	Passive	ONR is maturing a Solid State Laser (SSL) technology through the SSL-Technology Maturation program
Naval Postgraduate School (NPS)	Active	NPS is both interested in atmospheric effects and laser performance research to inform academia.
United States Navy Armed Forces	Passive	The Navy is currently investing in multiple projects that are advancing High Energy Laser technology for warfighter use in the maritime environment.
NSWC Port Hueneme	Active	NSWC PHD has been designated by NAVSEA to be the Directed Energy ISEA for the Navy and also possesses the Point Mugu Sea Range as part of Naval Base Ventura County.
NAWC Point Mugu	Passive	NAWC Point Mugu Is responsible for the Mugu Sea Range where HEL testing has been conducted in the recent past and will be used for HEL weapon system testing and evaluation in the future.

B. HIGH-LEVEL REQUIREMENTS

High-level requirements were captured in initial meetings among Naval Postgraduate School (NPS) system engineers and the stakeholders including NSWC Port Hueneme Directed Energy Projects Group, SPAWAR Atmospherics Group, and the NPS Systems Engineering Department. These high-level requirements identify the need to collect laser performance measurements. Similarly, the test bed will incorporate atmospheric and meteorological data for the test site, gathered continuously throughout the year to serve as a baseline and at the time of the test event. The environmental data gathered during a test event will be specific to the planned laser propagation path.

The user community will have a number of questions as they develop their respective test and evaluations strategies. Questions similar to the ones listed below will be used determine whether the test bed is a suitable environment and can provide the necessary resources to satisfy customer needs.

- Can the test bed subject the system under test to maritime conditions representative of operational environment such as customer required sea states?
- Can the test bed present a swarm of targets, both surface and airborne at customer specified ranges and altitudes?
- Is the test bed capable of supporting data collection during events using inherent sensors resident on the range?
- Can the test bed control an area of operation sufficient to meet customer testing needs?
- Can the test range secure facilities to support laser testing for the duration of test event?
- Can platforms within the test bed provide adequate SWaP provisions to support requirements of various systems under test?

These preceding bulleted list of questions will arise as a result of further discussions on the necessities required to execute a HEL test program and are reflected in the functional requirements (Chapter II, Section C).

High-level need statements shown in Table 2 outline the various configurations of the test platforms and the parameters requested by the stakeholders.

Table 2. High-Level Requirements

No.	High-Level Requirement Statements
-	Test bed shall provide the capability to augment standard MRTFB resources with performance and effectiveness data collection methods during DE systems test events involving radiating from…
1	… a ship to a single or multiple surface targets.
2	… a ship to a single or multiple airborne targets.
3	… a ship to a static target.
4	… a shore-based facility to a single or multiple airborne targets.
5	… a shore-based facility to a single or multiple surface targets.
6	… an airborne platform to a static target.
7	… an airborne platform to a single or multiple surface target.
8	… an airborne platform to a single or multiple airborne target.

Developed from initial meetings with the stakeholders, the HEL System Functional Block Diagram (Figure 11) depicts the inputs, controls, mechanisms, and outputs of the HEL test bed. The controls involved in the HEL test bed are described in Assumptions and Constraints (Chapter I, Section D). The platforms utilized by the HEL test bed are shown in Table 3 with additional required mechanisms discussed in Range Capabilities (Chapter II, Section E). Additional descriptions of the output, methods for collecting this data, and associated instrumentation are provided in HEL Test Bed Toolset (Chapter IV).

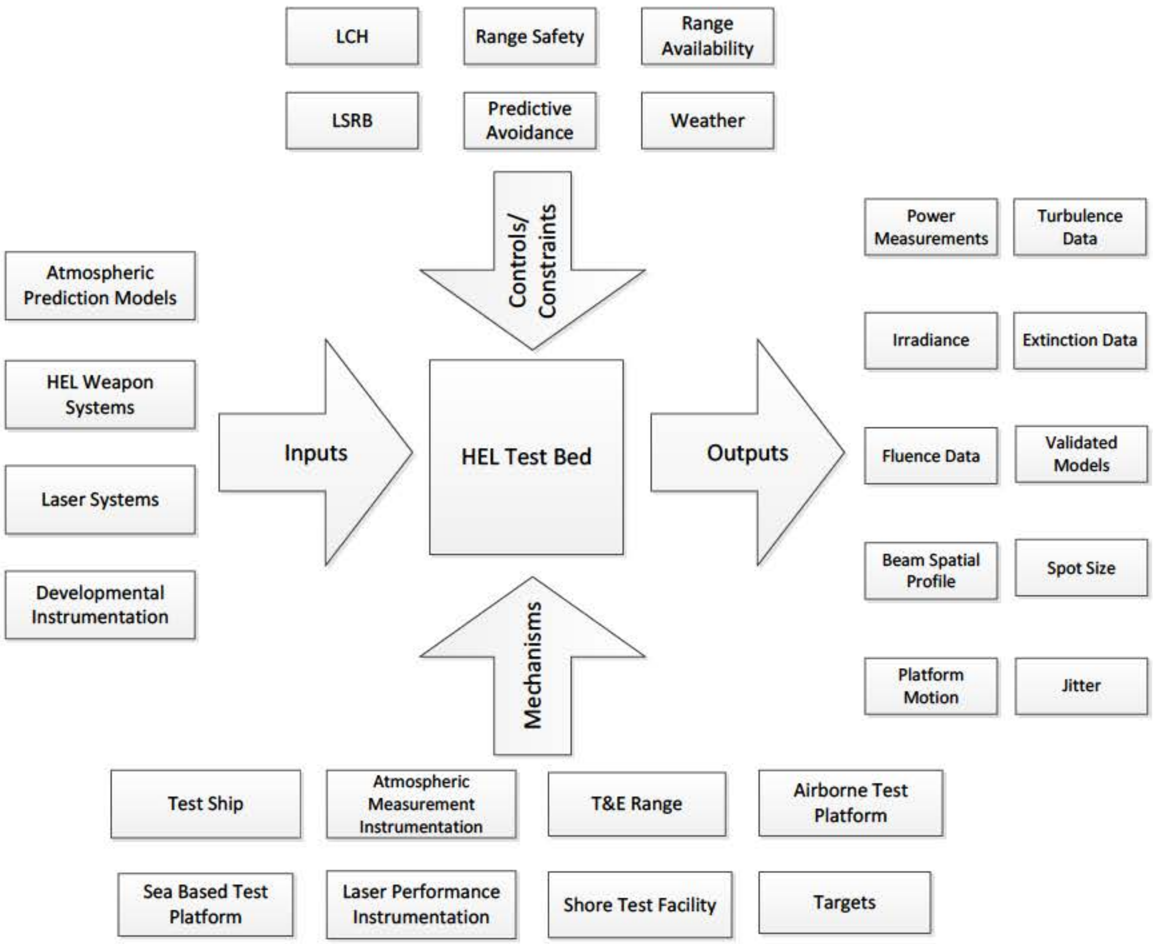


Figure 11. HEL System Context Diagram

From the list of stakeholder needs, several key platforms were identified that must be employed in order to establish a relevant test bed in a maritime environment. The HEL test bed will be composed of the Family of Systems (FoS) described in Table 3 that will come together to meet stakeholder requirements. Each of the platforms identified can act as an independent entity; the set of identified platforms (systems) can then be configured as required depending on what test scenario has been selected to be run.

Table 3. Test Environment Platforms

Platform	Capability
Surface Platform	Dynamic test asset capable of housing a test article and providing the necessary support infrastructure such as data collection, target tracking, cooling, and power
Surface Target	Dynamic platform capable of staying afloat in a maritime environment and collecting test data
Airborne Platform	Highly dynamic test asset capable of unmanned flight while supporting the operation of an onboard test article
Airborne Target	Highly dynamic platform capable of unmanned flight and collection of test data
Static Platform	Static installation located near the shore capable of housing a test article and providing the necessary support infrastructure such as data collection, target tracking, cooling, and power
Static Target	Static installation located near the shore, capable of collecting test data

The identified test bed needs were transformed into a conceptual test scenario and was reviewed with the stakeholders. After multiple iterations, the concept of operations displayed in the OV-1 comprised of various test events involving lasing and environmental data collection, as seen in Figure 12. Aerial, surface, and shore platforms will serve as targets for the designated test ship. Aerial and surface platforms will also be utilized as targets by static installation, shown near the shore. Both static installations and the test ship will aid in gathering environmental data that can be incorporated into laser testing results to accurately evaluate laser performance. The stakeholder needs and the resulting OV-1 will be further decomposed (Chapter II, Section C).

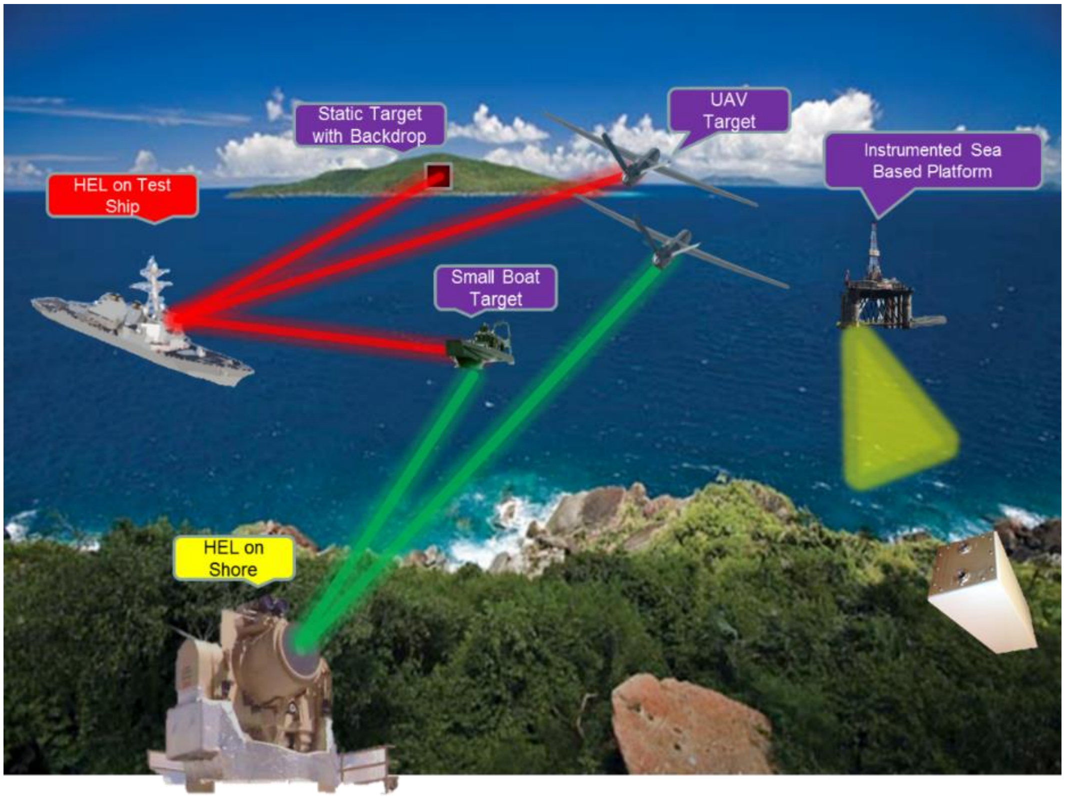


Figure 12. HEL Test Bed OV-1

C. FUNCTIONAL REQUIREMENTS

The high-level requirements, previously described in Table 2, have been used to derive the specific functional requirements for testing and evaluating HEL weapons systems and atmospheric characterization tools, in concurrence with the stated mission objectives. The derived functional requirements of the test bed are listed in Table 4. The test environment platforms, outlined in Table 3, have been allocated according to the necessary equipment for the staging of each functional requirement test. Utilization of test platforms will allow for prototype equipment, which has typically already undergone testing in a laboratory, to be verified in a relevant maritime environment and provide repeatable, consistent testing and demonstrations. The various configurations of the test environment platforms are described in further detail within the Concept of Operations (Chapter II, Section D). Ideally, coordination of multiple test requirements could be scheduled to leverage scenarios that utilize similar test platforms, thus integrating the individual tests into a single overall test (Blanchard & Fabrycky 2011). For example, a test scenario involving a HEL system firing from a test ship could provide the opportunity to engage both surface platforms and UAVs, efficiently using funds, personnel and range availability.

Table 4. Functional Requirements

WBS Code	Functional Requirements
1	**Test bed shall provide the capability to support laser test events from ship to shore**
	Test bed shall provide…
1.1	…a test ship capable of supporting laser test events at sea
1.2	…a static installation capable of supporting laser test events at shore
1.3	…capability to collect laser performance metrics at the aperture
1.4	…capability to collect laser performance metrics at range
1.5	…atmospheric data for all laser propagation events on the range
1.6	…meteorological data for all laser propagation events on the range
1.7	…facilities for gathering all external event data
2	**Test bed shall provide the capability to support laser test events from ship to surface platform**
	Test bed shall provide…
2.1	…a test ship capable of supporting laser test events at sea
2.2	…one or more surface platform capable of supporting laser test events at sea
2.3	…capability to collect laser performance metrics at the aperture
2.4	…capability to collect laser performance metrics at range
2.5	…atmospheric data for all laser propagation events on the range
2.6	…meteorological data for all laser propagation events on the range
2.7	…facilities for gathering all external event data
3	**Test bed shall provide the capability to support laser test events from ship to airborne platform**
	Test bed shall provide…
3.1	…a test ship capable of supporting laser test events at sea
3.2	…one or more airborne platform capable of supporting laser test events
3.3	…capability to collect laser performance metrics at the aperture
3.4	…capability to collect laser performance metrics at range
3.5	…atmospheric data for all laser propagation events on the range
3.6	…meteorological data for all laser propagation events on the range
3.7	…facilities for gathering all external event data

WBS Code	Functional Requirements
4	**Test bed shall provide the capability to support laser test events from shore to surface platform**
	Test bed shall provide…
4.1	…a static installation capable of supporting laser test events at shore
4.2	…one or more surface platform capable of supporting laser test events at sea
4.3	…capability to collect laser performance metrics at the aperture
4.4	…capability to collect laser performance metrics at range
4.5	…atmospheric data for all laser propagation events on the range
4.6	…meteorological data for all laser propagation events on the range
4.7	…facilities for gathering all external event data
5	**Test bed shall provide the capability to support laser test events from shore to airborne platform**
	Test bed shall provide…
5.1	…a static installation capable of supporting laser test events at shore
5.2	…one or more airborne platform capable of supporting laser test events
5.3	…capability to collect laser performance metrics at the aperture
5.4	…capability to collect laser performance metrics at range
5.5	…atmospheric data for all laser propagation events on the range
5.6	…meteorological data for all laser propagation events on the range
5.7	…facilities for gathering all external event data
6	**Test bed shall provide the capability to support laser test events from airborne platform to shore**
	Test bed shall provide…
6.1	…an aerial platform capable of supporting laser test events
6.2	…a static installation capable of supporting laser test events at shore
6.3	…capability to collect laser performance metrics at the aperture
6.4	…capability to collect laser performance metrics at range
6.5	…atmospheric data for all laser propagation events on the range
6.6	…meteorological data for all laser propagation events on the range
6.7	…facilities for gathering all external event data
7	**Test bed shall provide the capability to support laser test events from airborne platform to surface**
	Test bed shall provide…
7.1	…an aerial platform capable of supporting laser test events
7.2	…one or more surface platform capable of supporting laser test events at sea
7.3	…capability to collect laser performance metrics at the aperture
7.4	…capability to collect laser performance metrics at range

WBS Code	Functional Requirements
7.5	…atmospheric data for all laser propagation events on the range
7.6	…meteorological data for all laser propagation events on the range
7.7	…facilities for gathering all external event data
8	**Test bed shall provide the capability to support laser test events from airborne platform to airborne platform**
	Test bed shall provide…
8.1	… an aerial platform capable of supporting laser test events
8.2	… one or more airborne platform capable of supporting laser weapons during laser test events
8.3	…capability to collect laser performance metrics at the aperture
8.4	…capability to collect laser performance metrics at range
8.5	…atmospheric data for all laser propagation events on the range
8.6	…meteorological data for all laser propagation events on the range
8.7	…facilities for gathering all external event data

The performance metrics called out in the high-level requirements have been decomposed into individual metrics, as shown in Table 5 and Table 6, to serve as MOPs for the system under test that will be collected by the test bed. Laser performance metrics have been defined as operating characteristics or system functions that can typically be measured at the aperture. Effectiveness factors are based on the actual effectiveness and efficiency in relation to mission scenarios, with the understanding that the system will operate in accordance with the stated performance specifications (Blanchard & Fabrycky 2011). The MOPs that are focused on were chosen due to the constraints they place on laser performance and their implications on beam propagation (Nielsen 1994). Detailed descriptions of these metrics can be found in the HEL Test Bed Tool Introduction (Chapter IV).

Table 5. Laser Performance Measurements at Aperture

No.	Laser Performance Measurements at Aperture
1	Irradiance
2	Beam spatial profile
3	Fluence
4	Total power
5	Jitter
6	Wavelength

Table 6. Laser Performance Measurements at Range

No.	Laser Performance Measurements at Range
1	Irradiance
2	Beam spatial profile
3	Fluence
4	Total power
5	Jitter
6	Power-in-the-bucket
7	Spot Size

Due to the interaction of HEL systems with the gases and suspended particulate matter that comprise the atmosphere, the laser beam may be subject to scattering and absorption, resulting in energy losses and decreased effectiveness (Nielson 1994). To calculate these losses and the associated reductions in laser effectiveness, various atmospheric and meteorological data will be gathered at the test site during the test event and throughout the year. This data includes extinction, turbulence, atmospheric pressure, humidity, temperature, wind speed and direction, as listed in Table 7 and Table 8.

Table 7. Atmospheric Data at Test Site

No.	Atmospheric Data Collected by Test Bed
1	Extinction data along the propagation path at the test site
2	Turbulence data along the propagation path at the test site
3	Current atmospheric data with regard to the laser propagation path at the time of the laser test event
4	Atmospheric data at the laser test site gathered throughout the year
5	Atmospheric prediction models with regard to the laser propagation path of the test event

Table 8. Meteorological Data at Test Site

No.	Meteorological Data collected by Test Bed
1	Pressure with regard to the laser propagation path at the time of the laser test event
2	Temperature with regard to the laser propagation path at the time of the laser test event
3	Wind speed & direction with regard to the laser propagation path at the time of the laser test event
4	Humidity with regard to the laser propagation path at the time of the laser test event
5	Current meteorological data with regard to the laser propagation path at the time of the laser test event
6	Meteorological data of the laser test event site gathered throughout the year
7	Meteorological prediction models with regard to the laser propagation path of the test event

Furthermore, the standard to which these measurements will be taken will be defined by the various stakeholders, whether it be sample size to satisfy design of experiments requirements, or data resolution to satisfy the modeling and simulation community. The extent to which these questions are answered will vary on a case-by-case basis depending on test goals and unique emergent requirements.

D. CONCEPT OF OPERATIONS

HEL weapon systems have the potential to be utilized in a wide variety of engagement scenarios in theater. As a complement to the Close-In Weapon System (CIWS) and the manned .50 Cal machine gun, the effectiveness of the HEL weapon system in providing protection from the threat of small surface craft and UAVs needs to be tested.

When addressing a high flying Intelligence, Surveillance, Reconnaissance (ISR) threat, a HEL system would be engaging targets at varying altitudes up to 60,000 feet flying at potentially high velocities up to 350 knots. Variable sea states require accurate target tracking and beam director stabilization to compensate. Measurements of tracking jitter, mount jitter, and beam jitter will be performed both at the laser and at the target when applicable. Similarly, there might be the need to measure irradiance and fluence both at the aperture of the HEL and at the target to provide system performance and effectiveness data.

From an environmental aspect, the close vicinity of the water surface to hostile surface craft and surface skimming missiles exacerbates the impacts of turbulence and extinction on the HEL beam. The extinction of the beam can be attributed to the absorption and scattering properties of salt and water particles near the surface of the ocean. Turbulence and aerosols diminish as the beam path increases in altitude leading to less distortion and extinction. As such, it is desirable to gather specific data concerning the meteorological conditions during live fire engagements.

The following subsections list example test and evaluation scenarios that the laser test bed would need to facilitate in order to fully assess HEL system capabilities. There are many other considerations, not discussed herein to manage scope and time constraints, such as target types and range regulations that must be addressed before assessment can be executed. It is assumed that the range designated as a HEL test facility will have approval to perform developmental testing of HELs.

The following scenarios are certainly not comprehensive but attempt to be representative of some of the possible test scenarios desired by stakeholders. The test bed is described herein as a developmental asset, but there is no apparent reason that the range performing these tests could not support integrated Developmental and Operational T&E as well.

1. Ship to Shore, Air, and Surface Targets

There is no indication that Navy surface combatants will be using lasers to engage targets on land, but there is a necessity to perform this test on a test range. Customers may want to test HEL capabilities in a controlled environment by reducing the amount of variables involved. Over ocean testing introduces maritime factors that might not be conducive to initial testing objectives. Performing tests on land provides the testers the opportunity to gather data using relatively stable conditions capable of facilitating various measurements that would not otherwise be practical when evaluating HEL performance. For example, a ball calorimeter needs to reside on a stable platform in order to gather accurate data such as irradiance and fluence described in Chapter IV, Section C.

Figure 13 depicts a possible configuration of an exercise involving a test ship and a sea-based platform. This platform could be anything from a land mass controlled by the range to a fixed test platform anchored at sea. The platform will provide a means of evaluating the HEL's ability to maintain its intended aim-point while being subjected to the sea-state, wind, and other environmental factors.

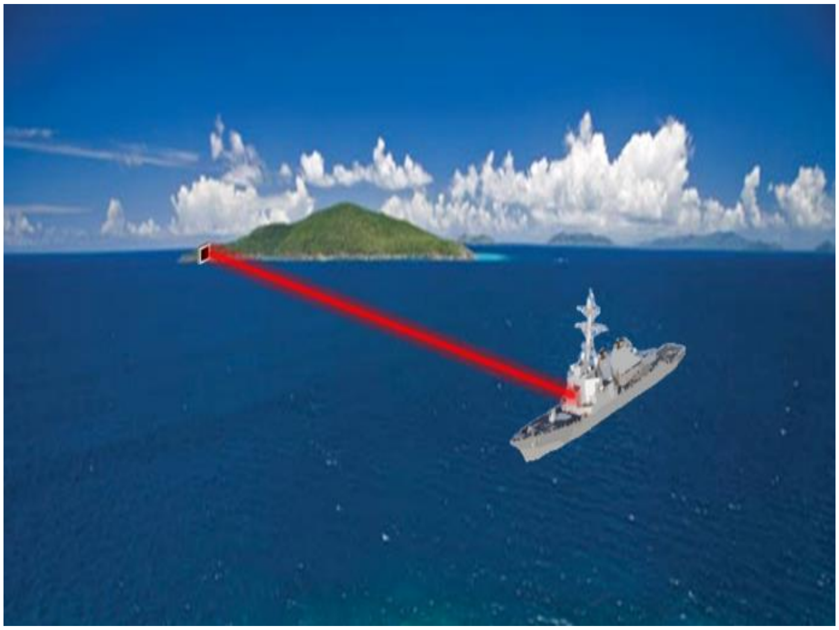


Figure 13. HEL Ship-to-Shore

Figure 14 depicts a live fire test event with a laser weapon installed aboard a test ship engaging two target UAVs flying in a raid configuration. Unmanned Aerial Systems (UASs) are the primary HEL targets of interest (ONR 2012). Operating UAVs is assumed to be an inherent capability of any range that intends on testing HELs.

Currently, there are efforts underway to develop HEL measurement instrumentation capable of being installed aboard UAV targets. With instrumentation onboard, evaluators will have increased capability to gather real-time HEL system performance data that will play a key role in determining if the system is ready to transition to a program of record.

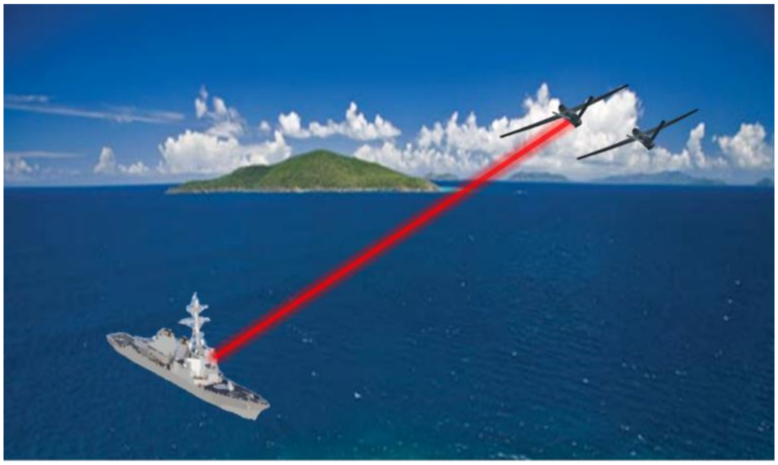


Figure 14. HEL Ship-to-Air

The secondary targets of interest are small boats which pose a significant threat to U.S. ships operating in foreign waters (ONR 2012) The Navy announced in the spring of 2013 that the Laser Weapon System (LaWS) would be deployed in the Persian Gulf to evaluate shipboard lasers in an operations setting against swarming boats and swarming UAVs (O'Rourke 2014). The ability to test HEL effectiveness against a small boat in a maritime environment is clearly a requirement for the T&E community and test ranges.

Figure 15 shows a swarm of small surface craft moving inbound toward a test ship outfitted with a HEL. These boats may need to be outfitted with ordinance or sensors to be representative of the operational threat. One or more of these targets can have instrumentation installed onboard to gather laser performance data (Chapter IV) during the event.

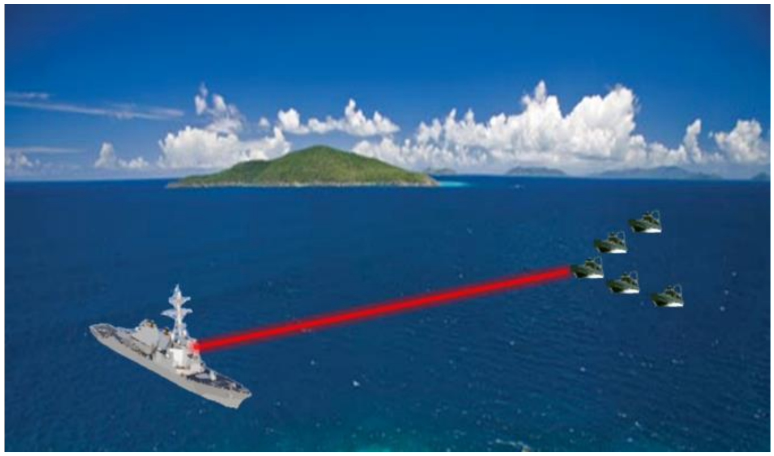


Figure 15. HEL Ship-to-Surface

2. Shore to Shore, Surface, and Air Targets

A key element in predicting laser performance is accomplished by creating models that determine the atmospheric and meteorological effects that will impact laser weapon system effectiveness. This analysis is done by taking measurements of the environment over a period of time or by using existing meteorological data. In order to validate new systems or employ validated systems for testing, the range should be capable of supporting Light Detection and Ranging (LIDAR) or two-sided atmospheric instrumentation for extended periods of time. The scenario in Figure 16 is best suited for two stable platforms such as adjacent shore facilities or shore to a stable sea-based platform.

Figure 16. HEL Shore-to-Shore

Shore-to-surface tests for small surface targets originates from the need to ensure that the laser, tracking, and control systems adhere to design criteria, meet performance objectives, and satisfy safety requirements. Currently, research does not suggest that HELs are desired for these operational engagements. However, these tests are meant to identify and reduce risks and demonstrate capability by limiting the variables of the environment with which they will be tested. This scenario will require that the range provides a location near the water that is approved for HEL operation and the ability to anchor or remotely operate a small boat as the customer desires (Figure 17).

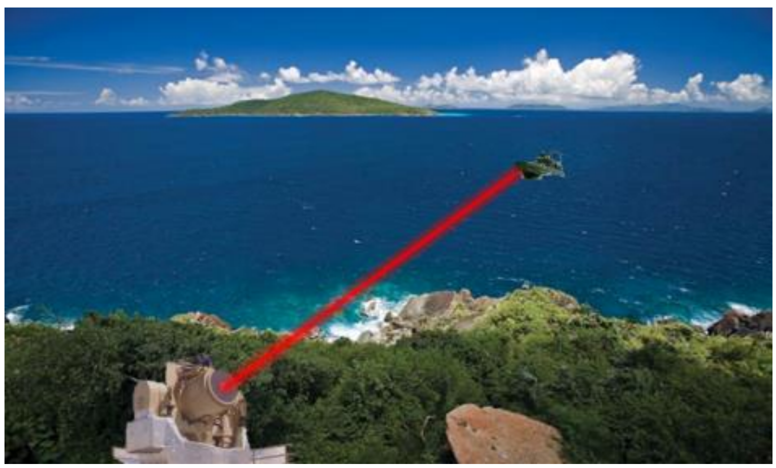


Figure 17. HEL Shore-to-Surface

Requirements to test a laser propagating from shore-to-air targets stem from the same capability demonstration and risk reduction needs of the shore-to-surface tests. These tests also provide a means for the Navy to obtain measurements from target UAVs that are placed in a dynamic environment, representative of the operational environment, and gather useful data during system development. However, payload limitations for instrumentation reduce the amount of data that can be obtained on a UAV. Shore-to-air scenarios are opportunities for the weapon system to demonstrate tracking and system performance using a UAV and a fixed shore-site to operate the laser. Figure 18 illustrates a possible engagement scenario between multiple UAVs and the laser weapon. The flight profile for the UAVs could be head-on, crossing, or some combination of these.

Figure 18. HEL Shore-to-Air

3. Air to Surface, Air, and Shore Targets

With the Airborne Laser (ABL) program coming to an end in 2012, the need for a range to conduct tests with ABL weapon systems has diminished. Advances in technology could change this in the near future by reducing the total size and weight of laser systems, which was a major challenge for previous systems. The Navy recently cancelled an initiative to develop a laser weapon to be mounted aboard a rotary wing aircraft. These efforts, though recently cancelled, suggest that there may again be a need to support testing of HELs aboard airborne platforms in the future.

When the need for airborne laser testing does arrive, there will be similar scenarios that the test bed will have to facilitate. A shore facility is needed that will host various laser performance instrumentation in order to validate the weapon system. The limitation of airborne target mounted instrumentation requires that a fixed platform be used.

The same scenarios exist for airborne systems that are present for surface lasers. In accordance with its current Navy force protection role, helicopters would likely employ an airborne laser system for the same purpose as surface mounted laser systems and would require that they be tested against small boats (Figure 19) and potentially low altitude UAVs as well.

Airborne lasers employed aboard a large military aircraft, such as an AC-130, like the Advanced Tactical Laser (ATL), are intended to be used against ballistic missiles and could potentially be used against high altitude UAVs considering their rapid proliferation (Figure 20).

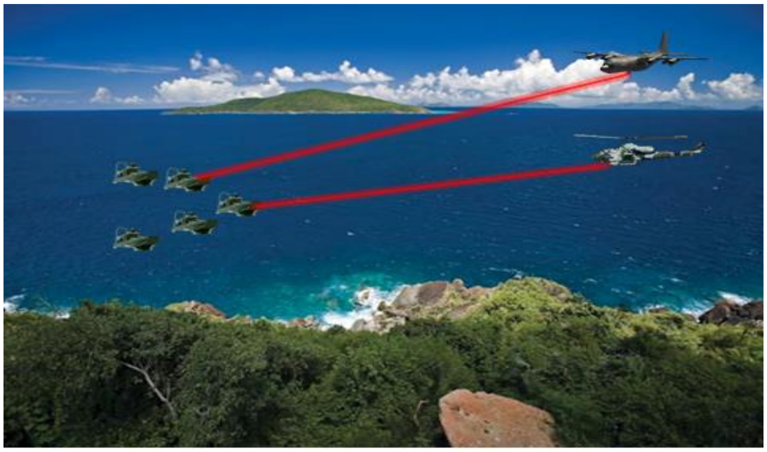


Figure 19. HEL Air-to-Surface

Figure 20. HEL Air-to-Air

E. RANGE CAPABILITIES

Range capabilities include the resources and attributes of the test site to support the effective and safe evolution of a HEL test event. These resources and attributes include safety control measures, facilities, personnel, test articles, and the inherent topography of the HEL test bed.

1. Range Resources

Range resources described within this document are assumed capabilities and assets that any prospective MRTFB would possess in order to facilitate a HEL test bed. This is in no way a comprehensive list but should cover some of the major aspects per MIL-HDBK-828B to meet stakeholder requirements.

a. Land, Air, and Sea Space Control

Control measures should be implemented to ensure the safe operation of a HEL test event for land, sea, and air testing scenarios. For any HEL test bed, range maps, elevation data, nautical charts, and airspace maps should be available to determine range boundaries, firing lanes and locations, populated areas, target locations, backstops, and no fire areas.

Ground-to-air laser events might require coordination with external activities to safely employ a laser. HELs that operate continuously, aimed up and above the horizon, and are not terminated (e.g., via a backstop, natural or man-made) should operate in coordination with the Federal Aviation Administration (FAA) and Laser Clearinghouse (LCH). Special Use Airspace (SUA) coordination might be required for HEL testing activity 45 meters above ground level via designation of restricted airspace, Controlled Firing Areas (CFAs), a Military Operations Area (MOA), and/or warning areas.

Any sources of reflection and obstructions including, but not limited to, mirrors, standing water, glossy surfaces, and ice, should be absent from range operations or have mitigations in place to ensure safety of all personnel involved in the testing. An example of air-to-ground reflection from standing water is shown in Figure 21. In addition to direct beam exposure, these reflections pose a risk to personnel and might cause bodily harm or injury, particularly to the eyes and skin. An example of reflected beam exposure is shown in Figure 22. As such, access control during HEL testing events should be communicated via Notice to Mariners (NOMAR) and Notice to Airmen (NOTAM) (MIL-HDBK-828B 2011).

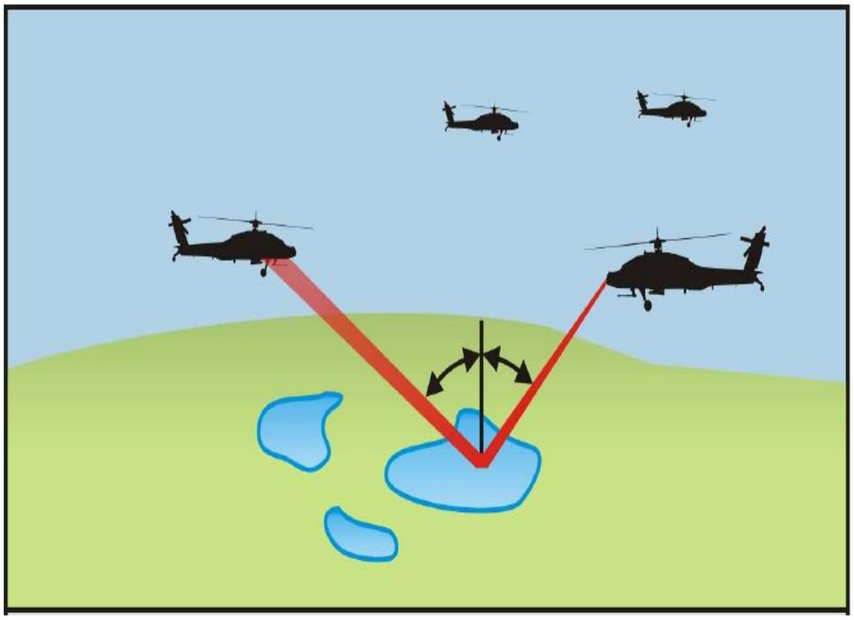


Figure 21. Potential Laser Reflection from Standing Water (from Department of Defense 2011)

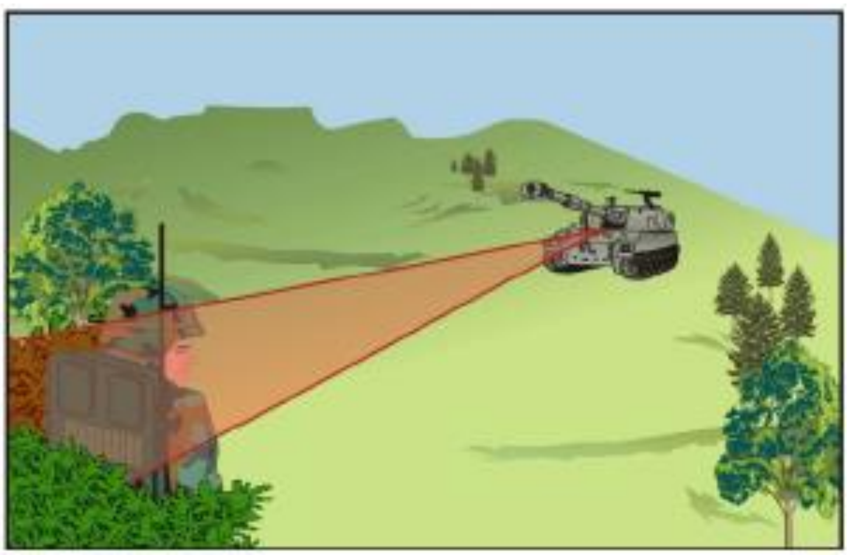


Figure 22. Reflected Beam Exposure (from Department of Defense 2011)

b. Facilities

The intended range location should possess facilities to support both field work and administrative requirements of personnel. Access control measures should be available to restrict access, as appropriate, to both field and administrative spaces (e.g., fences, warning signs, encrypted door locks, etc.) to ensure personnel do not enter the keep-out zones generated by the Nominal Ocular Hazard Distance (NOHD) for the HEL under test.

Nearby populated military and civilian buildings, terrain, and wildlife influenced by the HEL test event shall be accounted for and evaluated for potential impact and safety risks. Administrative controls to reduce risk in the form of Standard Operating Procedures (SOPs) should be available by the facility to provide guidance on the employment and operation of HEL systems including, but not limited to, use of Personal Protective Equipment (PPE), delineation of range responsibilities, and provisions for communicating and scheduling laser events with surrounding personnel.

c. Test Article Assets

Test articles include the supportive elements to the HEL under test to ensure a safe and secure lasing event. The composition of these elements is dependent on the needs of the particular HEL system and the objectives of the test. A comprehensive test bed should be able to support shore, surface, and air HEL testing requirements for the given system. Key supportive elements include the following:

- instrumentation
- control centers facilities
- air, surface, and shore targets (e.g., HSMSTs, UAVs, tow platforms)
- air, surface, and shore support platforms
- telemetry systems
- operational personnel
- land, air, and sea-space to act as ranges.

One example of a range is located at NBVC Point Mugu. The location consists of about 36,000 square miles of controlled sea and air space. Air, surface, and ballistic targets are available with facilities for the handling and storage of ordnance. It is staffed with about 300 people consisting of civilian, military, and contractor personnel.

The use of decommissioned platforms is extremely costly and typically does not model a threat with any realism. Dedicated and reusable targets that can mimic operational scenarios are of great value. Surface target systems include the QST-35 to act as a High Speed Maneuvering Surface Target (HSMST) and the SL-20 for target recovery. Sample aerial targets articles include the BQM-74 (subsonic) and GQM-163A (supersonic) missiles. Range support aircraft includes the C-130 and NP-3D. Some of these assets are fully remote controlled such as the 17m QST-35 and or can be employed by unmanned platforms. Some of these test assets are shown in Figure 23.

Figure 23. Sample Test Targets and Range Support Aircraft (after Matzos 2006, Tarantola 2013, and Dr. TRX 2013)

San Nicolas Island and Santa Cruz Island are two additional examples of potential HEL test bed locations. Like NBVC, Point Mugu, which resides along the central California coast, these locations are geographically situated to support testing and can provide support instrumentation, as required. Sample instrumentation support is as follows:

- tracking radars
- photo-optics support

- telemetry reception
- microwave communication
- frequency surveillance.

d. Personnel

Range personnel include institutional, installation, and unit range authorities. Each group plays key roles in establishing a safe and effective HEL test event. As such, their designations should be made in writing and the roles and responsibilities should be understood by all parties.

Institutional authorities provide the oversight to installation personnel to aid in reducing risk during HEL test events by providing guidance to regulations, laser use publications, training requirements, and laser range certification. Per MIL-HDBK-828B, the institutional authority conducts the following:

- Gathers and review preliminary data.
- Performs preliminary data analysis.
- Conducts a range survey (verify boundaries, firing lanes, targets).
- Analyzes data, identify risk, and recommend risk mitigation.
- Compiles and report results.

Installation range authorities implement the guidance given by the institutional authorities and are responsible for maintaining range operations, enforcing risk controls, evaluating laser systems used in the range, and communicating its use to the affected public. To gain certification per MIL-HDBK-828B, the installation range authority provides the following to the institutional range authorities:

- Reviews the laser systems to be employed.
- Identifies range boundaries.
- Identifies airspace restrictions.
- Identifies laser firing area/line/points.

- Identifies laser target area/line/points.
- Identifies Laser Surface Danger Zone (LSDZ) limitations.
- Provides a range map.
- Identifies points of interest (towers, structures, roadways).

Unit range authorities generate laser training plans for the HEL test event and submit the proposal to the laser range authority. In addition to requesting approval of laser training plans, the unit range authority should also perform a safety and operations inspection of the range prior to use. It conducts in-briefs to affected personnel including laser operators and observers. The MIL-HDBK-828B calls out the duties of the unit range authority which includes, but is not limited to, the following:

- Review training to be accomplished against local operating procedures.
- Select a range whose laser range certification supports the laser system(s) to be used and training exercise to be accomplished.
- Identify targets, laser firing area/line/points, laser to target orientation, and orbit points that can be supported by the laser surface danger zone.
- Identify ground personnel locations.
- Identify PPE requirements.
- Identify communications requirements.
- Identify emergency response procedures.

The aforementioned groups are integral to the range and the number of personnel should be sufficient to allow for a wide spectrum and size of testing events. The groups do not include those personnel required for a specific laser system and might require augmentation depending on specific laser requirements.

2. Range Attributes

In addition to the various resources the HEL test bed range must have access to it must also contain various innate characteristics that make it capable of HEL testing. Chapter II, Sections C and D discussed the various functional requirements and operational scenarios that the test bed must fulfill. These requirements and scenarios derived from stakeholder feedback were the basis for selecting three mandatory attributes examined as follows: the HEL test bed range must have a pier, must have a facility near the shore, and also must meet certain geographical parameters such as the existence of a backstop. For example, a pier and shore facilities would be needed to support ship to shore, air, and surface exercises. Figure 24 shows a basic layout of the range attributes that are required for successful HEL testing.

Figure 24. Essential Range Attributes (from Vzvrev 2014)

Although there are countless other characteristics that may be considered when discussing range attributes, only three were selected for this section because other attributes are assumed inherent for any proposed HEL test range location. For instance, range ceiling is a characteristic that could be discussed, but the assumption in this section is that characteristics such as this will already be approved and inherent to the proposed range location. Other elements of the test range like adequate range volume and proper permissions (i.e., FAA and LCH) are already assumed to be in place.

a. Pier (for Test Ship)

Based on the various scenarios to conduct HEL testing from onboard a test ship, the selected range must have a pier for docking the test ship. The pier must be located such that it is easily accessible by land for support personnel that will be required to board the ship frequently, or on short notice. The pier must also be large enough to allow for several temporary facilities to be installed on site, as required. For instance, a temporary guard shack may be required for sensitive testing that will be ongoing for an extended period of time. Auxiliary power may be needed to support different test events, or repair issues that might arise. Also, the pier must be wide enough to support crane operations for loading/unloading equipment onboard the ship. An image of a pier with external support resources on site is shown below in Figure 25.

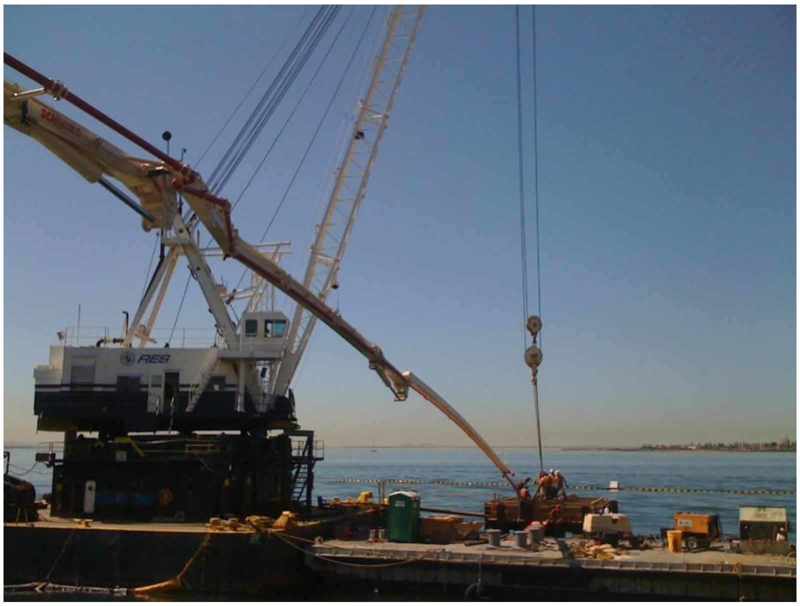


Figure 25. Pier External Support Resources (from R.E. Staite Engineering 2012)

b. Facility Near Shore

As depicted in Figure 12 (HEL Test Bed OV-1), there are scenarios that involve HEL test data collection to and from the shore. For the instances where there will be lasing occurring from a test platform to the shore, the requirements discussed (Chapter II, Section E) must be followed.

c. Topographical Layout

Due to safety concerns when conducting HEL testing, it is essential that the test range possesses backstop. A backstop is necessary when conducting HEL testing to ensure that lasing terminates and does not accidentally propagate further than expected. This may cause harm to personnel or other non-targets residing in the vicinity of the test bed location and well beyond. Backstops are a significant test range attribute because they will provide laser propagation control that will prevent any part of the beam that exceeds the Maximum Permissible Exposure (MPE) from leaving a controlled area. In instances where the laser beam range exceeds the Nominal Ocular Hazard Distance (NOHD), the hazard distance becomes the distance from the laser source to the selected backstop (natural or artificial) (Range Safety Group 1998).

III. ARCHITECTURE DEVELOPMENT

The tailored SE staircase model performed continued with architecture development (Figure 26) which defined the system concept as well as the functions and corresponding physical components necessary to meet the requirements.

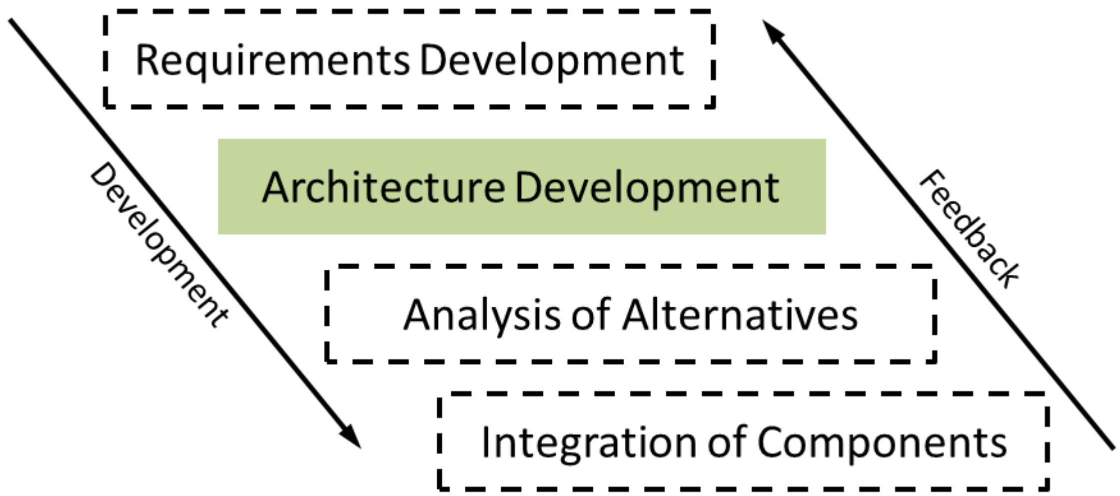


Figure 26. Tailored SE Process: Architecture Development Stage

A. DEVELOPMENT METHODOLOGY

The architecture of the high energy laser test bed is one of the most important aspects of this study. The technology and instrumentation involving HEL and DE weapons will continue to develop. The testing locations and participants may vary over time; however, a well-developed, modular architecture will provide longevity to this study. As such, two important aspects of the test bed architecture are black box theory and modularity.

1. Black Box Theory

The black box theory is a concept of taking a complex system and viewing it at an abstract level. The system inputs and resulting outputs are viewed, but the complex internal workings of the system are ignored. Utilizing the typical block diagram structure, the inputs and outputs are identified while the component itself is shown as a "black box" without description or detail, hence the name (Figure 27).

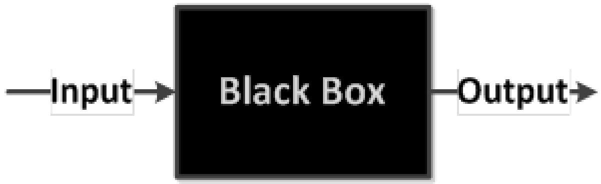


Figure 27. Generic Black Box (from Green, Seeney, and Stracener 2014)

Black box theory has several benefits when applied to SE. Systems engineering typically deals with the design, development, and management of very complex systems. Often the focus is on improving the performance, reliability, and cost of these systems. Black boxes offer a scalable tool to address a complex system at the various levels. By focusing on the inputs and outputs, design of the test bed can focus on connections and integration rather than on the components themselves. Additionally, design decisions can be made that will improve the overall performance and effectiveness of the system without the need to be concerned with the lower level details of each component.

Page-Jones developed a structured approach to system design based on black box usage,

> The starting point is the problem statement and the focus is on what the system needs to do versus how to do it. Analysis starts with a high level abstraction of the system and uses the system purpose to guide the nature of the solution. The goal of structured design, as advanced by Page-Jones, is to reduce complexity through partitioning the system into smaller pieces through the use of black boxes. The rationale for this is straightforward. First, black boxes provide an external description of behavior. Second, the black box has known inputs and outputs. It represents a function; i.e., the transforming of inputs to outputs though how the function actually performs the transformation is unknown at this level of abstraction. Finally, black boxes are hierarchal in nature thus boundaries and interfaces are established within each level of decomposition. (Green, Sweeney, and Stracener 2014)

As described in this quote, the usefulness of applying black box theory to the test bed architecture becomes very clear. It allows for the reduction of the complexity of the architecture by focusing on the high-level abstraction of the system, the functions that need to be performed by the test bed, and leaves out the details on how the various subsystems will perform these functions. Another reason black box theory fits well in the development of the test bed architecture, as described in this quote, is that the inputs and outputs of the various subsystems are known without having to have knowledge of the inner workings of each system. This makes applying black box theory straightforward and easy to implement.

Additionally, Page-Jones provides guidelines which were followed to assist in the design process:

- Each black box should solve one well-defined piece of the problem.
- Partitioning is done such that each black box is easy to understand (i.e., a function).
- Partitioning is done only to connect related elements of the problem.
- Partitioning should assume that the connections are as simple as possible to ensure the independence of the black box.

These guidelines were followed when developing the High Energy Laser test bed architecture and applying black box theory to the design. The test bed will contain numerous complex performance and atmospheric measuring tools. The inner working of these components, while important to the overall effectiveness of the test bed, are not necessarily important when it comes to taking requirements and developing the functional and physical models of the test bed. Identified as "suites," these black boxes allow the focus to be on overall design and integration rather than on what specific components will be used. See Figure 28 as an example.

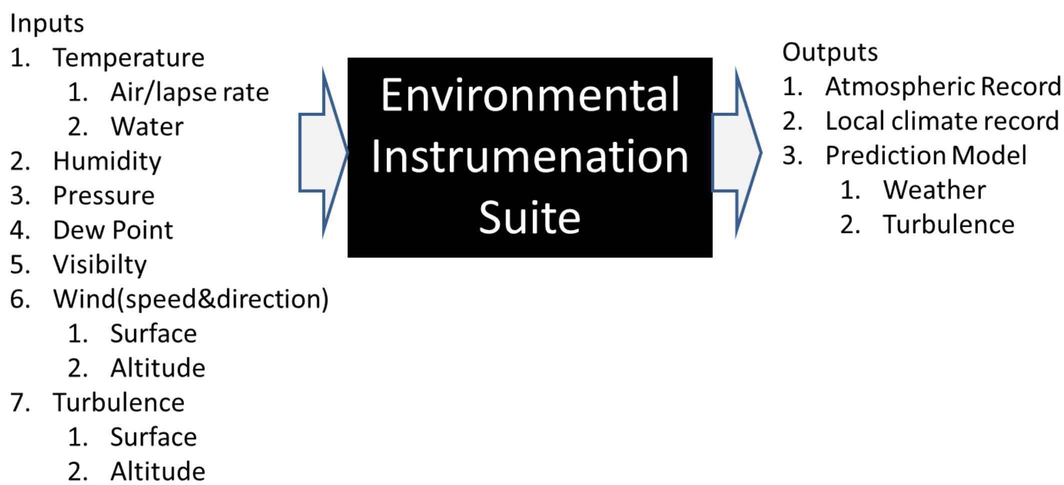


Figure 28. Environmental Instrumentation "Black Box"

Another reason for utilizing the black box methodology is its scalability. Black boxes allow the test bed scalability in its design, from high-levels of abstractness to more finite levels of concreteness. They also allow scalability in future construction of a physical test bed, allowing the builders to choose from multiple options that perform some or all of the specific functions.

This leads to a third reason for the use of black boxes. The fields of High Energy Lasers and Directed Energy are rapidly developing. The instrumentation and sensors used to gather data for HEL and DE testing are also changing. By using the flexibility of black boxes, a degree of longevity is included in this work, the test bed can evolve with the field. New sensors and instrumentation can be incorporated and integrated as they are developed. Lastly, black boxes assist in ensuring the test bed architecture maintains its most important aspect, modularity. The benefits of having a modular architecture are described in the following section.

2. Modularity

Modularity of the High Energy Laser test bed was an extremely important aspect that was carefully considered in the development of the test ted architecture. Modularity allows the test bed to be scalable and adaptable.

The first key characteristic that a modular architecture brings to the HEL test bed is scalability. The test bed architecture was designed to be implemented in various locations. These locations can consist of variable geography, weather, and climate as well as different owners, operators, and preexisting infrastructure. The modular architecture allows the size, scope, and cost of the test bed to be scaled to fit each location. Thus, the architecture can be equally applicable for a single static mounted solid state laser or a large mega-watt class chemical laser.

The second key characteristic that a modular architecture brings to the HEL test bed is adaptability. The field of HEL weapon systems is still relatively new. Performance and atmospheric measuring systems that are used in conjunction with laser weapon systems are rapidly evolving. A test bed architecture that could adapt to these rapidly changing systems is needed to prevent the architecture from quickly becoming obsolete. As new laser systems are developed and new test tools to measure performance and atmospheric conditions are produced, they can easily be implemented into the existing test bed architecture due to the modularity in design. As instrumentation evolves, the performance metrics will remain the same, which if modeled correctly, will allow for the evolution to take place without diminishing the modularity of the architecture.

Implementing modularity in the design of the HEL test bed was an important aspect that was carefully considered. The modularity aspect of the test bed will greatly increase the longevity of the significance this test bed will play in the Department of Defense and future laser programs.

B. FUNCTIONAL ARCHITECTURE

The functional architecture is a key component to the development of the HEL test bed. The functional architecture not only helps map out and clearly depict the various functions that will be executed within the HEL test bed, but it also helps ensure all stakeholder requirements will be met. The resulting functional decomposition from the requirements analysis was a vital component of the functional architecture development as will be discussed in the next section.

1. Functional Decomposition

Through stakeholder meetings, a list of requirements was derived from the stakeholder needs previously described (Chapter II, Section B and C). These stakeholder needs and requirements were translated into functions that make up the functional architecture of the HEL test bed. The Level 1 functions of the functional architecture were chosen to meet the thirteen stakeholder needs. The following is a list of the functional architecture Level 1 functions:

- Support Shipboard Laser Testing
- Support Shore Site Laser Testing
- Support Airborne Laser Testing

Shipboard testing consists of tests conducted for laser systems installed aboard the test ship. This test platform can also be used for early testing of laser systems intended to be mounted on submarines. Shore site laser testing consists of testing for laser systems installed onboard land vehicles which might also act as a cheaper alternative for early testing of laser systems that will eventually be installed onboard ships or aircrafts. Airborne laser testing using test aircraft includes testing for laser systems intended for both fixed wing aircraft and helicopters. These functions, and the resulting sub functions, will cover all of the needs of the HEL test bed that were discussed with stakeholders. These Level 1 functions were broken down further to address the derived requirements that were pulled from our stakeholder needs.

The three Level 1 functions, Support Shipboard Laser Testing, Support Shore Site Laser Testing, and Support Airborne Laser tasting, encompasses all laser testing that will be done from laser systems tested on the HEL test bed. These functions were each decomposed into nine Level 2 similar sub functions based on the type of testing that would be conducted from each platform. Support Shipboard Laser Testing decomposed into supporting ship to shore testing, ship to surface testing, and ship to air testing. Support Shore Site Laser Testing decomposed into supporting shore to shore testing, shore to surface testing, and shore to air testing. Lastly, Support Airborne Laser Testing decomposed into supporting air to shore testing, air to surface testing, and air to air testing.

Each of these specific testing functions were further decomposed into the various measurements that need to be gathered for each test event.

The nine functions that make up Level 2 of the functional architecture all decompose into the same three Level 3 functions. Each specific type of laser testing will require the collection of laser performance data and the collection of environmental data. Environmental data is collected throughout the range at the time the laser testing is conducted. These three third level functions are repeated in the functional architecture for each type of laser testing, and are decomposed further into Level 4 of the functional architecture.

The first function in Level 4 of the functional architecture, collect laser data at aperture, involves the task of collecting and recording data regarding the performance of the laser system under test at or near the aperture. Performance is a quantified measurement of various laser characteristics. The following are performance characteristics of the laser: beam spatial profile, irradiance, fluence, wavelength, spot size, jitter, and total power. These parameters quantify how well the unit under test performs, independent of its operating environment. While the environment (the atmosphere in particular) does have a significant impact on the effectiveness of a laser system, these variables are a glimpse of the laser system by itself. This data must be collected, recorded, and compiled for the various laser systems under test for personnel to fully evaluate it.

The second function in Level 4 of the functional architecture, collect laser data at range, involves the task of collecting and recording all data that has to do with the performance of the laser system under test at the target. The performance data at range is equally important, if not more important, than laser data at aperture. In addition to characterizing the laser performance at the target, this data will also assist in evaluating the environmental effects of the laser by comparing laser data at range to laser data at aperture.

The third and final function in Level 4 of the functional architecture, collect environmental data, consists of the collection of atmospheric data, meteorological data, and platform data. Tracking this data is important to stakeholders of laser systems due to the profound impact it can have on both the performance and effectiveness of lasers. As the laser beam propagates through the air, it simultaneously affects and is affected by the atmosphere. For example, thermal blooming changes the refractive index of the air, which subsequently affects its own attenuation. The high humidity of the maritime environment, especially when low over the water, also affects the beam. Atmospheric turbulence between the laser and its target also has a significant negative impact on laser performance and effectiveness, which is further discussed in Chapter IV, Section A. Gathering such data will help characterize how the laser system under test is affected by various atmospheric and meteorological conditions. It can also be factored into current modeling and simulation software to assist in further study. Additionally, it will facilitate further advances in the utilization of the environment in beam shaping, such as the use of adaptive optics.

The functions and sub functions of the functional architecture represent the direct and derived requirements from the initial stakeholder needs list. A test bed that is capable of supporting all of these functions will be capable of meeting current and future laser testing needs of the Navy.

2. Functional Architecture Diagram

The following figures will depict the functional architecture in a piecewise manner for clarity. The first diagram illustrates the three Level 1 functions that decompose the overall function of the HEL test bed, which is to Perform HEL Testing. Figure 29 represents the top level of the functional architecture.

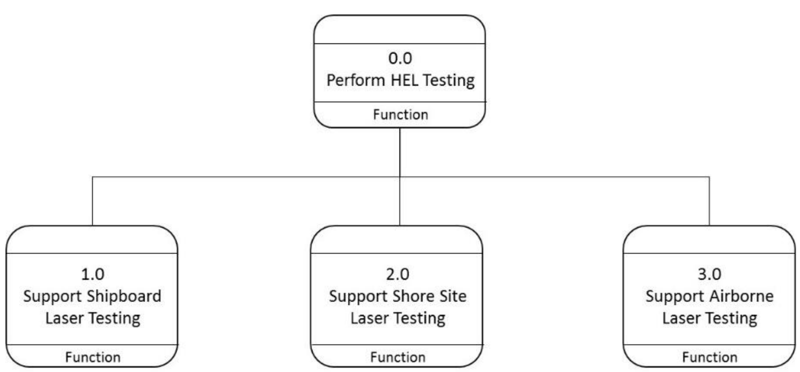


Figure 29. Top Level Functional Architecture

Figure 30 through Figure 32 illustrates the decomposition of the three top level functions shown in Figure 29. These three functions, and their respective decomposed functions in Level 2, represent the various types of laser testing that the HEL test bed must be capable of performing and the measurements that will be collected during these test events. All combinations of laser testing using a shore site, shipboard test platform, and airborne test platform are represented in this section of the functional architecture. The Level 3 functions depicting the data that will be collected during each event, laser data at aperture, laser data at range, and environmental data are depicted as well; however, they are only illustrated once in each figure. For simplicity in presentation, the Level 3 functions are not repeated for the other Level 2 functions in each diagram; however, the same sub functions apply to these functions.

Figure 30 depicts the breakdown of supporting shipboard laser testing. This three level breakdown illustrates the three types of laser testing that will be conducted from shipboard lasers, and the three sets of data that will be collected for each test scenario.

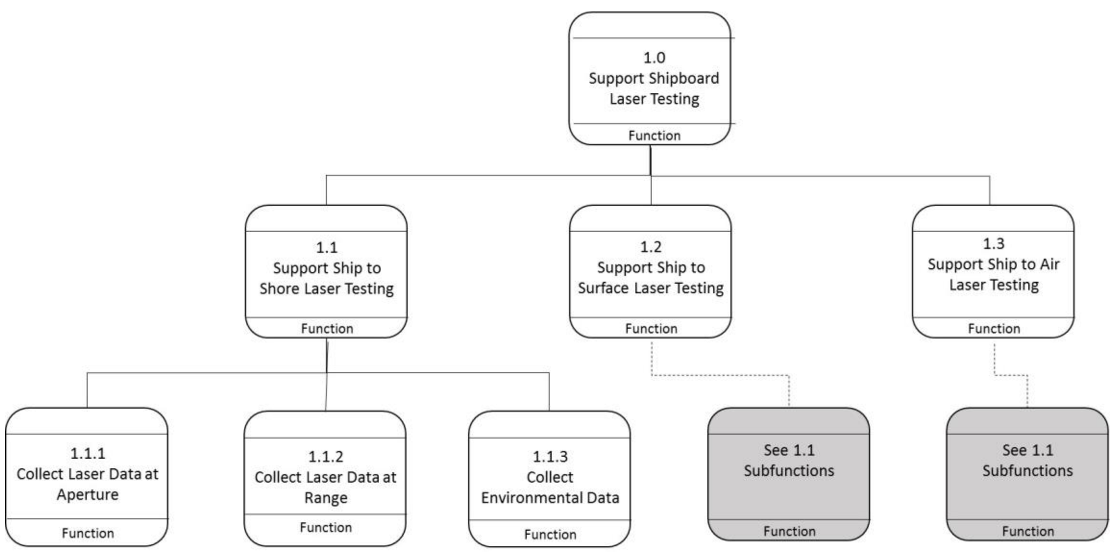


Figure 30. Support Shipboard Laser Testing Sub Functions

Figure 31 depicts the breakdown of supporting shore site laser testing. This three level breakdown also illustrates the three types of shore site laser testing as well as the data sets that will be collected for these tests.

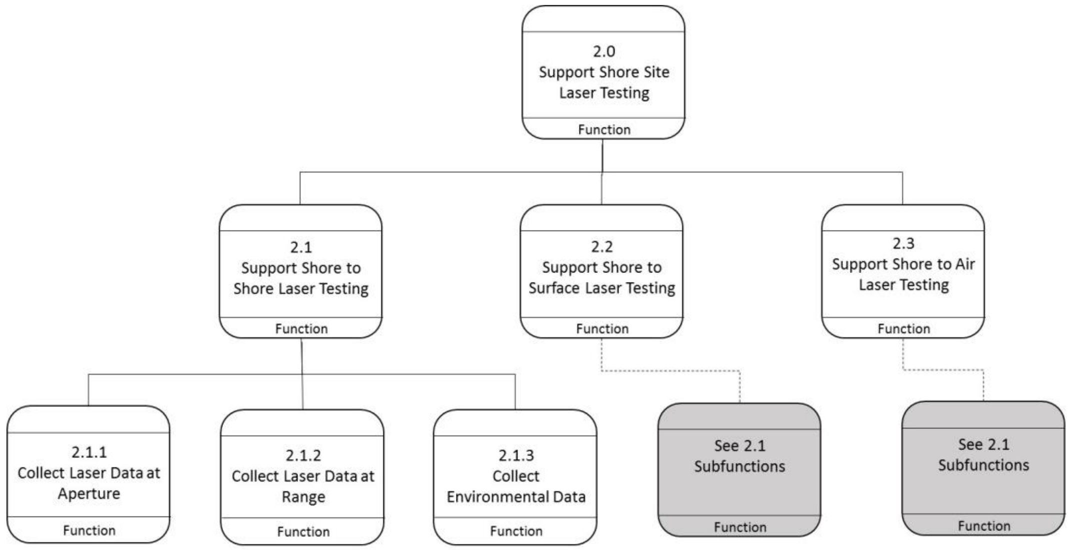


Figure 31. Support Shore Site Laser Testing Sub Functions

Figure 32 depicts the breakdown of supporting airborne laser testing, the three sub types of airborne laser testing, and the data sets that will be collected during this testing.

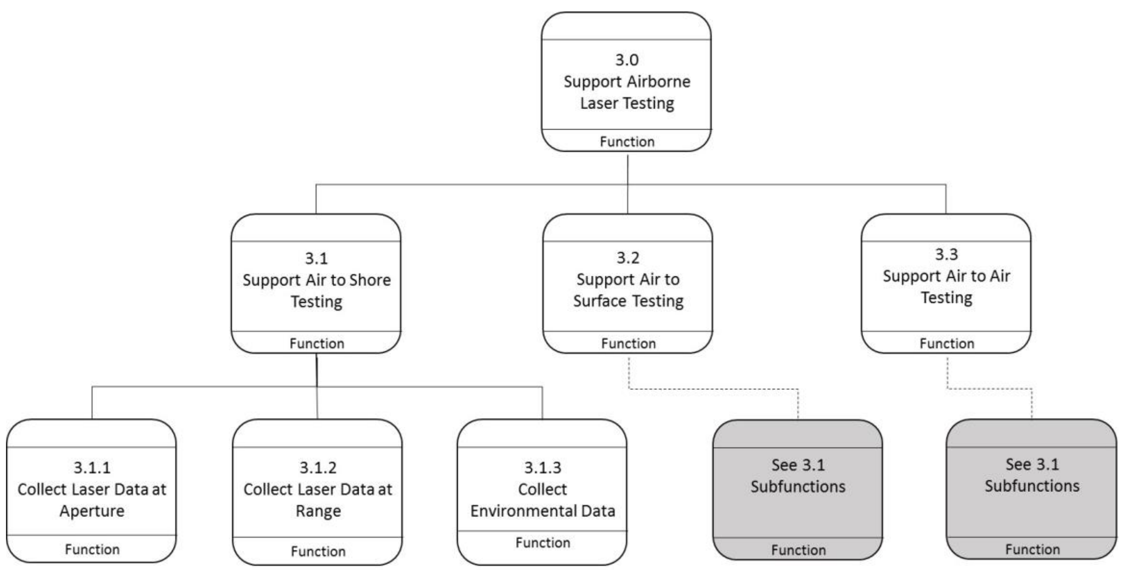


Figure 32. Support Airborne Laser Testing Sub Functions

Figure 33 through Figure 35 illustrate the breakdown of Level 3 functions of the functional architecture, collect laser data at aperture, collect laser data at range, and collect environmental data. Level 4 functions portray the various metrics that must be collected during all laser system testing to fully evaluate the performance of the laser system and the various environmental data that may affect the laser system. Once again, for simplicity in presentation, Level 4 functions shown only trace up to one Level 2 function (Function 1.1 in this case), but these measures will be collected for all laser testing executed on the HEL Test Bed. See Figure 33 through Figure 35 for the decomposition of one branch for collecting laser data at aperture, laser data at range, and environmental data.

Figure 33 breaks down the function of collecting laser data at aperture, illustrating the seven types of measurements that will be collected at aperture.

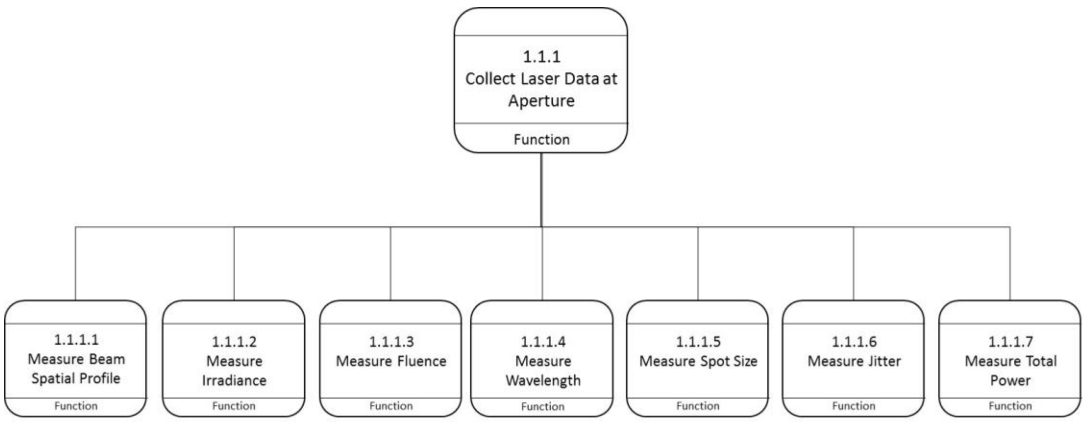


Figure 33. Collect Laser Data at Aperature Sub Functions

Figure 34 depicts the breakdown of collecting laser data at range, showing the six measurements that will be collected at range for laser testing.

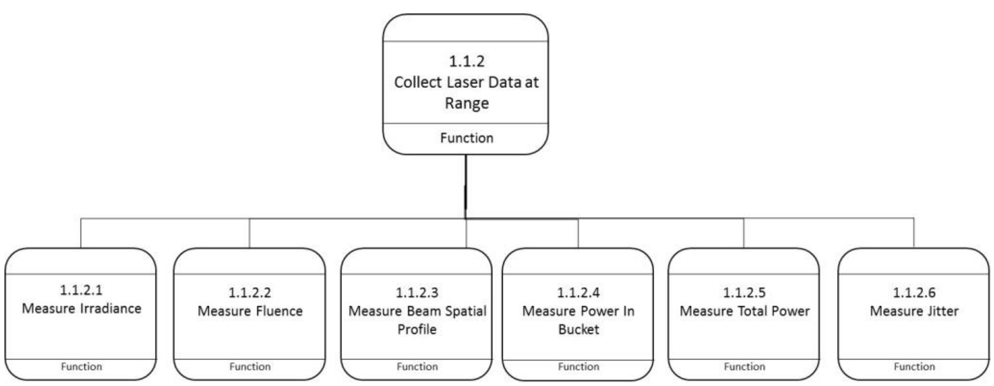


Figure 34. Collect Laser Data at Range Sub Functions

Figure 35 illustrates the breakdown of collecting environmental data. This function breaks down into two additional levels separating the atmospheric, meteorological, and platform data, along with the measurements collected for each.

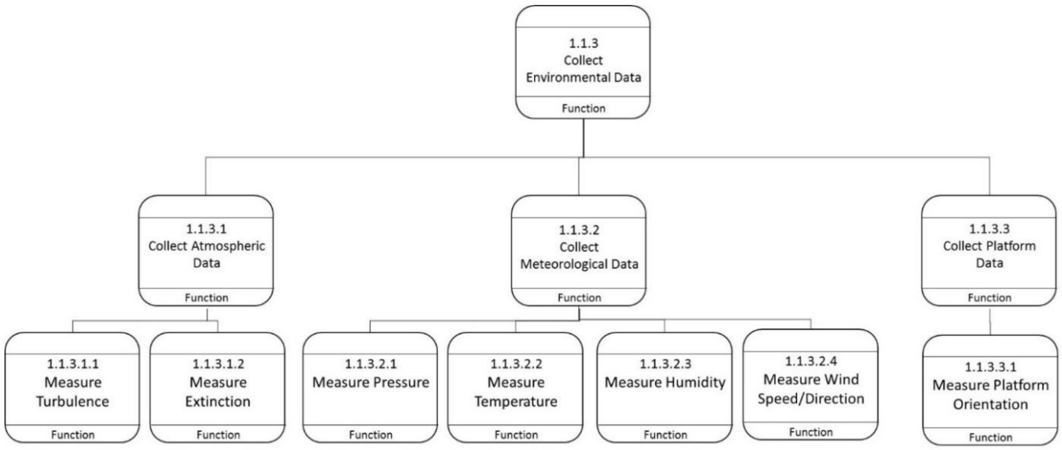


Figure 35. Collect Environmental Data Sub Functions

C. PHYSICAL ARCHITECTURE

The physical architecture was designed to consist of all of the necessary components to fulfill the decomposed functional requirements. It does this from a high level to allow for maximum flexibility in design by allowing for testing at various scales and of varying scope. The physical architecture consists of all range platforms, such as a test ship and sea-based platforms, in addition to the various instrumentation tool suites that are required to accomplish all test functions. The physical architecture elements are also required to measure and record all necessary data during test events to evaluate laser systems and contribute to the improvement of modeling and simulation of system performance. This physical architecture will tie into the functional architecture to create the allocated architecture of the HEL test bed.

1. Test Platforms

The first section of the physical architecture consists of the range and all of the test platforms that are necessary to have on the range to meet all airborne, shipboard, and shore site laser testing needs. These laser testing needs necessitate an area where testing can be accomplished outside a laboratory. Ideally, this range would consist of a test environment that is as operationally realistic as possible; where safety aspects are already in place, and infrastructure, such as buildings and power already exist.

The four major components that the range will consist of are a static test platform, test aircraft, test ship, and targets. These physical components of the range will allow for the full breadth of laser testing required by stakeholders. Any combination of laser testing involving shore, surface, and air with both stationary and maneuvering targets can be accomplished using these test platforms and components that make up the range.

The first component under the range in the physical architecture consists of a static test platform. The static test platform is comprised of a shore-based test facility and sea-based platforms. These components will be used for conducting laser testing to and from the shore. Shore-based testing could be used for both early stage testing for maritime laser systems as well as testing for land-based and vehicle-based laser systems for the marines.

The second component of the range consists of a test aircraft. The test aircraft will be used as the airborne laser test platform that laser systems can be mounted to for conducting laser testing from an aircraft to shore, surface, and air targets. The test aircraft must be capable of flying at a wide range of altitudes and speeds under load to meet all laser testing needs.

The third component of the range consists of a test ship. The test ship is a vital aspect of the test range for the U.S. Navy that will allow for various laser systems to be installed on an actual ship, increasing the fidelity and validity of test events, allowing for tests to be conducted in the most operationally realistic scenario as possible. In addition to improved testing, one of the ultimate goals of Navy HEL testing is to mount, man, and power a HEL on a ship. To prove this capability, a test ship is required. Ideally, it would be large enough to power multiple firings and house actual firing equipment and instrumentation. Consideration should be given regarding duration of tests and whether the ship contains suitable mess and berthing facilities for the test personnel and crew onboard the ship.

The fourth component of the range consists of targets. Targets consist of the various components that the lasers will be aimed at and fired upon: both static and mobile. In some scenarios, they will be static allowing for a myriad of instruments to gather data on the beam itself. These articles maximize control and safety while potentially minimizing cost. In other scenarios, the targets will be mobile such as small surface crafts or unmanned aerial vehicles (UAVs). These targets would represent the ultimate test goal of the HEL systems as these targets would simulate real world threats that the laser systems must be able to effectively defeat.

2. Test Tool Suites

The other major components of the HEL test bed that make up the physical architecture are the various test tool suites. The test bed will consist of an Aperture Instrumentation Suite, an At Range Instrumentation Suite, and an Environmental Instrumentation suite. All of these systems are required during laser test events to verify laser system functionality and meet all stakeholder needs.

The first tool suite of the HEL test bed is the Aperture Instrumentation Suite. This tool suite will focus on the sensors and instrumentation that characterizes and measures the performance of the laser at aperture. This tool suite consists of a target board with a high speed camera suite to measure beam spatial profile, spot size, and jitter, a calorimeter to measure irradiance and fluence, and a wavelength sensor.

The second tool suite of the HEL test bed is the At Range Instrumentation Suite. This tool suite will contain the sensors and instrumentation for determining laser performance at range. This tool suite consists of a Ball or Flat Plate Calorimeter to measure irradiance and fluence, a target board with a high speed camera suite to measure beam spatial profile, and a calorimeter and target board combination to measure power in the bucket.

The third tool suite of the HEL test bed is the Environmental Instrumentation Suite. This tool suite is used to measure all the environmental data in the proximity of the laser test and can be broken down into three separate tool suites: an Atmospheric Instrumentation Suite, a Meteorological Instrumentation Suite, and a Platform Instrumentation Suite. The

Atmospheric Instrumentation Suite consists of a C_n^2 sensor, an r_0 sensor, and a transmissometer. The Meteorological Instrumentation Suite consists of a pressure sensor, temperature sensor, humidity sensor, and wind sensor. The Platform Instrumentation Suite consists of a gyroscope and accelerometers used for measuring the orientation and movement of either the test ship or test aircraft during laser testing. The data collected by these tools will serve two main purposes. First, it will assist in the study of the laser itself as the environment has a profound effect on its transmission. Secondly, it will be used to improve current modeling and simulation capabilities. Modeling and simulation is discussed in Chapter IV, Section G.

By correlating the HEL-testing-specific measurements from the Atmospheric Instrumentation Suite to the much more common Meteorological Instrumentation Suite, it is possible to simulate and expand the test data derived from simple weather and almanac information. Ideally, and with a high fidelity model, it is possible to predict the effects of transmission and turbulence from simple weather data like temperature, pressure, and humidity.

Specific systems that meet the requirements of these various tools will not be identified in the architecture in order to increase the modularity and longevity of the HEL test bed architecture. Current systems that could possibly be used in the HEL test bed to satisfy the test tool suite requirements will be discussed in Chapter IV.

3. Physical Architecture Diagram

The following illustrations will depict the physical architecture, broken down into sections. The first diagram illustrates the top level of the physical architecture for the HEL test bed and shows the four major components that make up the test bed. See Figure 36 for the top level physical architecture.

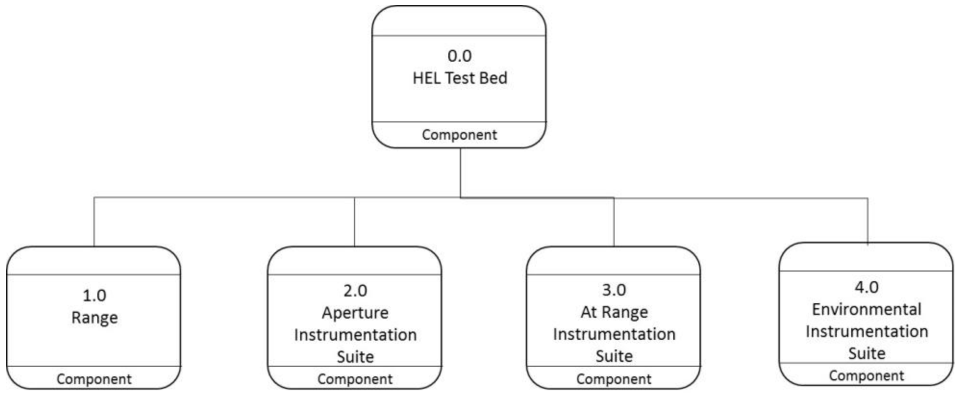


Figure 36. Top Level Physical Architecture

Figure 37 illustrates the next two levels of sub components that make up the first Level 1 physical component, the range. The range is composed of all of the test platforms and targets that are needed to conduct the wide array of possible laser tests. See Figure 37 for the range physical breakdown.

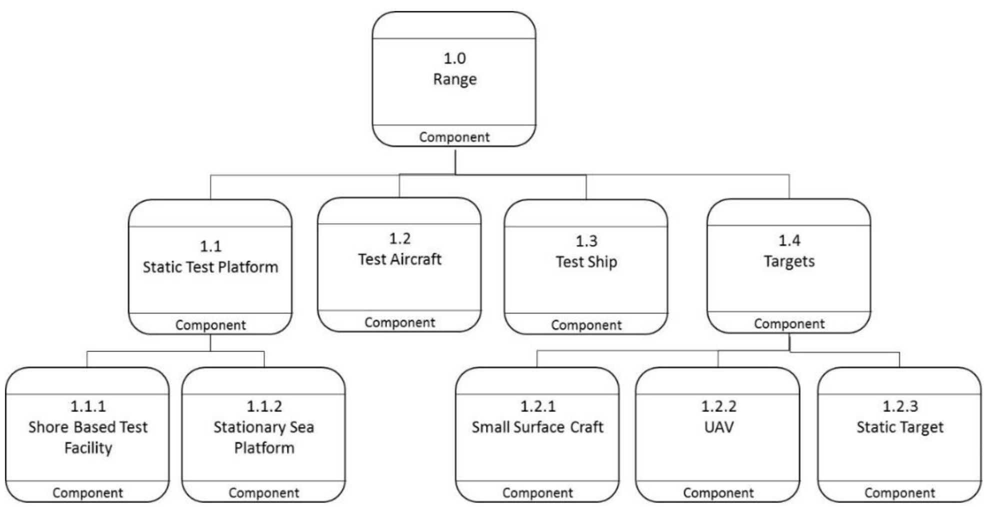


Figure 37. Range Physical Breakdown

Figure 38 through Figure 40 depicts the breakdown of the three Instrumentation Suites: Aperture, At Range, and the Environmental. These three instrumentation suites represent all of the measurements to be collected during test events to evaluate the laser system under test as well as fully define the environment to which the laser test is conducted. See Figure 38 through Figure 40 for the breakdown of the physical components that make up the three main instrumentation suites of the HEL test bed.

Figure 38 portrays the aperture instrumentation suite and the three components that make up this suite.

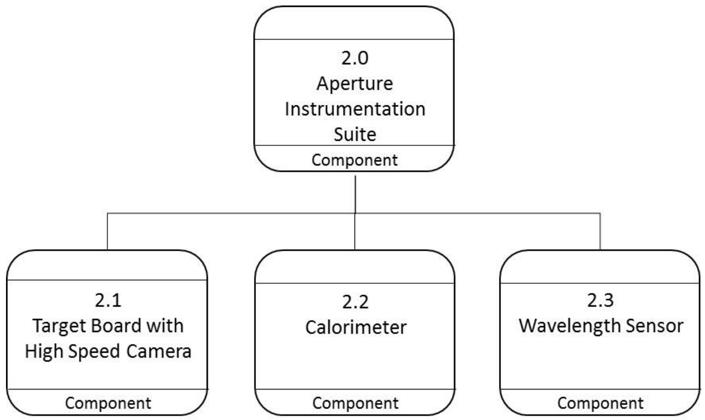


Figure 38. Aperture Instrumentation Suite Breakdown

Figure 39 portrays the At Range Instrumentation Suite, along with the three components the makeup that suite.

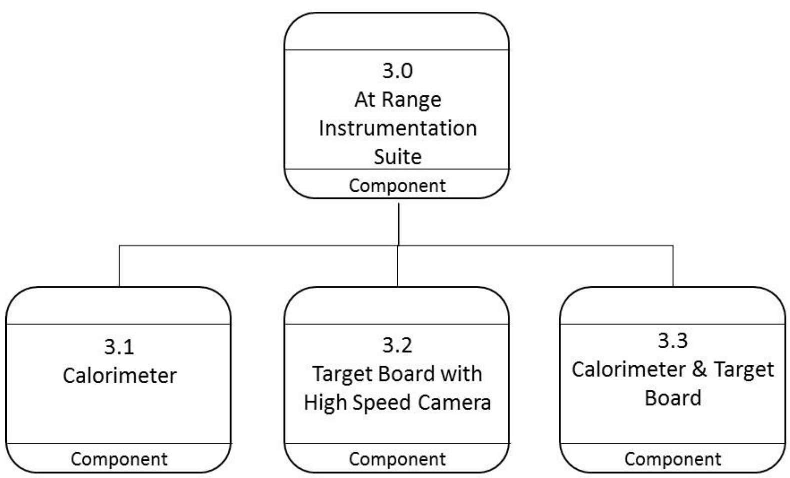


Figure 39. At Range Instrumentation Suite Breakdown

Figure 40 illustrates the Environmental Instrumentation Suite. This instrumentation suite breaks down into three additional instrumentation suites that are composed of various measurement tools.

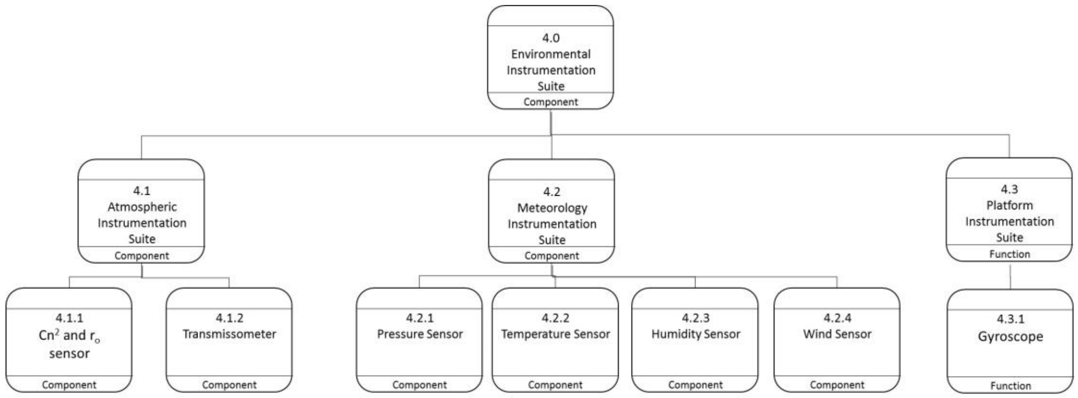


Figure 40. Environmental Instrumentation Suite Breakdown

D. ALLOCATED ARCHITECTURE

The allocated architecture combines the functional and physical architectures. Each physical component is assigned to a function. The allocated architecture lays out all of the components that the HEL test bed consists of, as well as all of the functions the HEL test bed is capable of supporting. Therefore, it is very easy to see if adjustments need to be made to the physical and functional architectures to meet all stakeholder needs. The allocated architecture will illustrate if there are any components of the physical architecture that are redundant or are not needed by having components that do not map to any functions. The allocated architecture will also show if there are any functions that need to be performed but do not have any corresponding physical components. The DoDAF 1.5 architecture framework was used in the development of the allocated architecture.

1. Integration of Functional and Physical Architecture

The physical architecture consists of several components that are broken out in a hierarchical fashion. The lowest level components of each branch of the physical architecture encompass all of the above components in the architecture. Therefore, only the lowest level components of each branch of the physical architecture were used to map into the functional architecture. For example, instead of trying to map the physical component, targets, to a function, the three sub components that make up targets, small surface craft, UAV, and static target were the components used in the mapping of functions for the allocated architecture. This same method was used for all branches of the physical architecture.

The mapping of components to functions starts at the second level of the allocated architecture. The function of supporting shipboard laser testing requires the physical component of a test ship. Supporting shore site laser testing utilizes the shore-based test facility, and supporting airborne laser testing requires the use of a test aircraft. The next level of the allocated architecture takes each one of these general test scenarios and breaks it down further. The various components needed to support each type of shipboard laser testing, shore site laser testing, and airborne laser testing were mapped out as well.

The next section of the allocated architecture maps out all the test tools in the three Instrumentation Suites to the characteristic that they are measuring in the functional architecture. The Collect Laser Performance function is allocated to the Laser Performance Instrumentation Suite. This allocates each required function to components used for performance measurement. The Aperture and At Range Tool Suites, which consists of various target boards, various calorimeters, and wavelength sensors, were mapped to all of the required functions of measuring beam spatial profile, irradiance, fluence, wavelength, spot size, jitter, power in bucket, and total power. The last part of the allocated architecture consists of the Environmental Instrumentation Suite, which consists of all of the atmospheric tools, meteorological tools, and the various measurements that each of these tools performs.

2. Allocated Architectural Diagram

The diagrams in this section illustrating the allocated architecture are, once again, broken up by sections for readability and comprehension. This architecture was built from the functional architecture but with the addition of the physical components associated to each function. The allocated architecture diagrams show the functional decomposition at the same time as the physical component breakdown, while illustrating which functions are performed by which components. Similar to the functional architecture, repeated branches of the allocated architecture are not depicted in the diagrams for simplicity in presentation. Only one instance of the performance and environmental functions are depicted; however, mapping from the physical components to the functions shown for one leg of the architecture can be repeated for all of the other legs. See Figure 41 through Figure 47 for the various allocated architecture diagrams.

Figure 41 depicts the top level of the allocated architecture, showing the components and functions of the three major laser test cases.

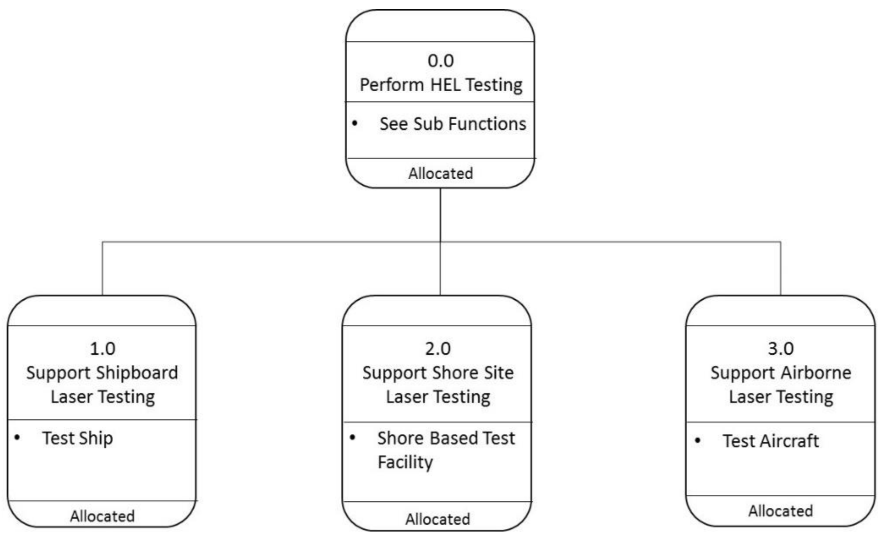


Figure 41. HEL Test Bed Top Level Allocated Architecture

Figure 42 portrays the allocated architecture breakdown of specifically shipboard laser testing. Once again repeated branches are not illustrated here.

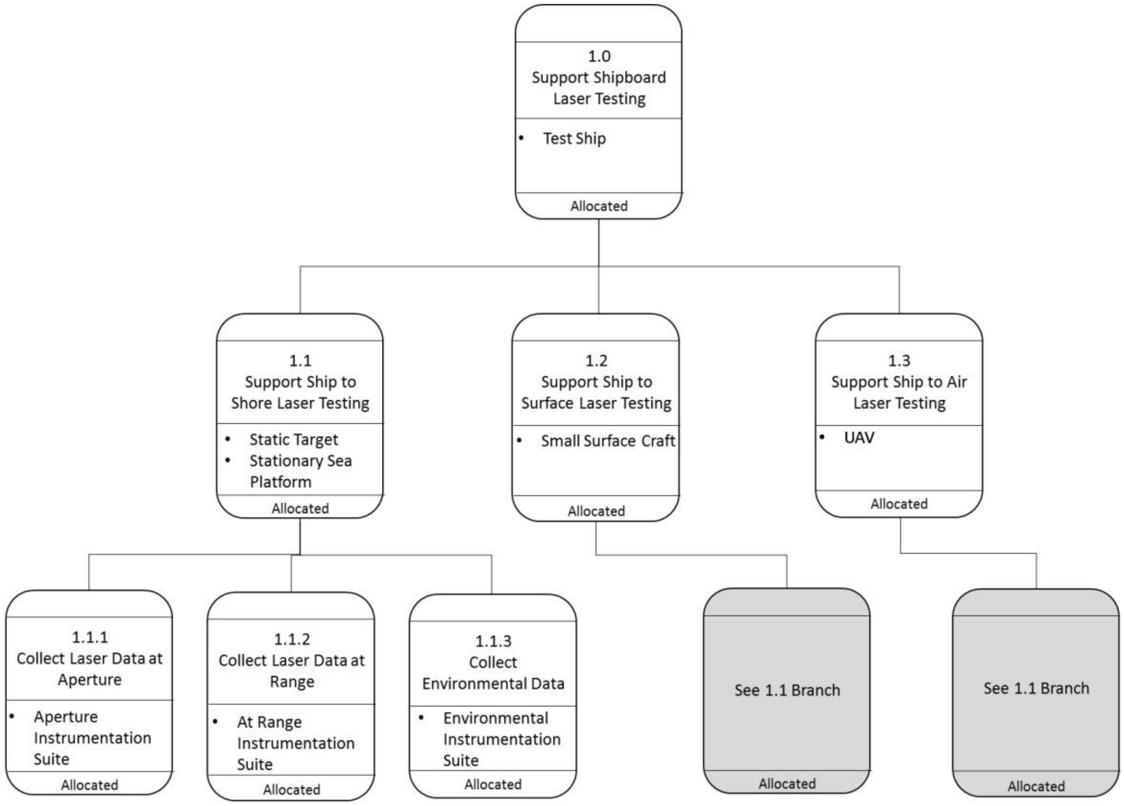


Figure 42. Shipboard Laser Testing Allocated Architecture

Figure 43 portrays the shore site laser testing portion of the allocated architecture and the various sub functions and components.

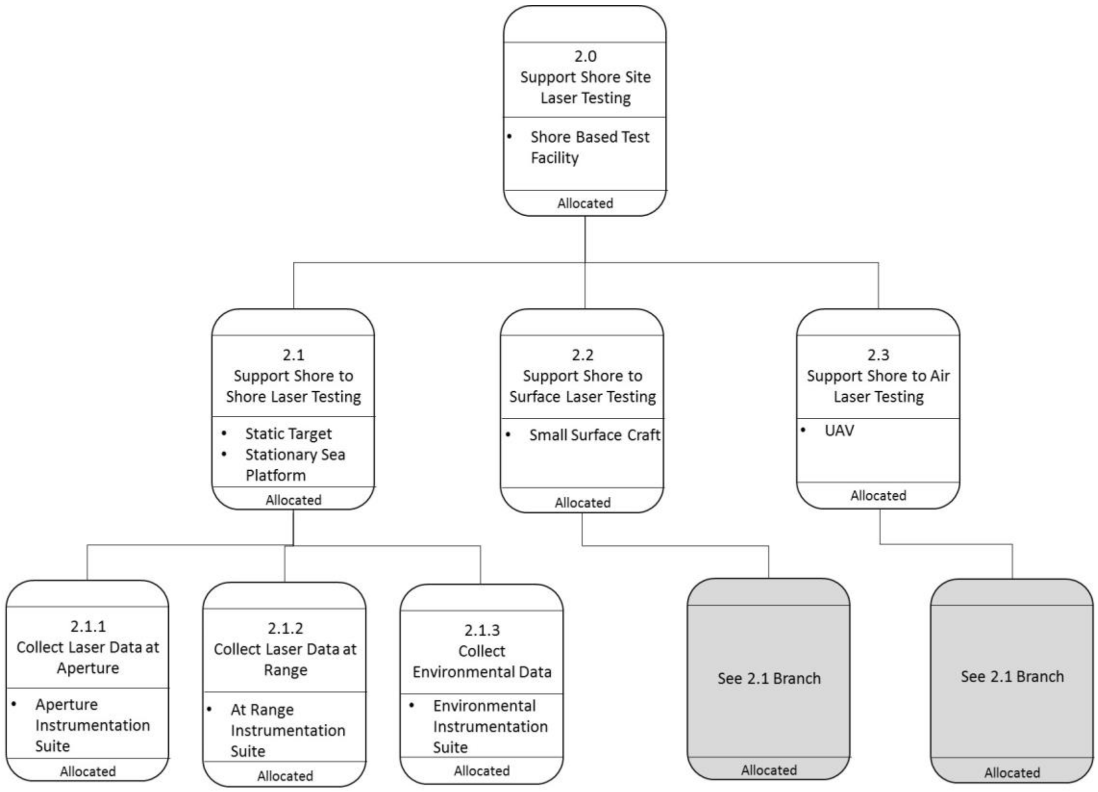


Figure 43. Shore Site Laser Testing Allocated Architecture

Figure 44 illustrates the airborne laser testing portion of the allocated architecture, which follows a similar format to shipboard and shore site laser testing.

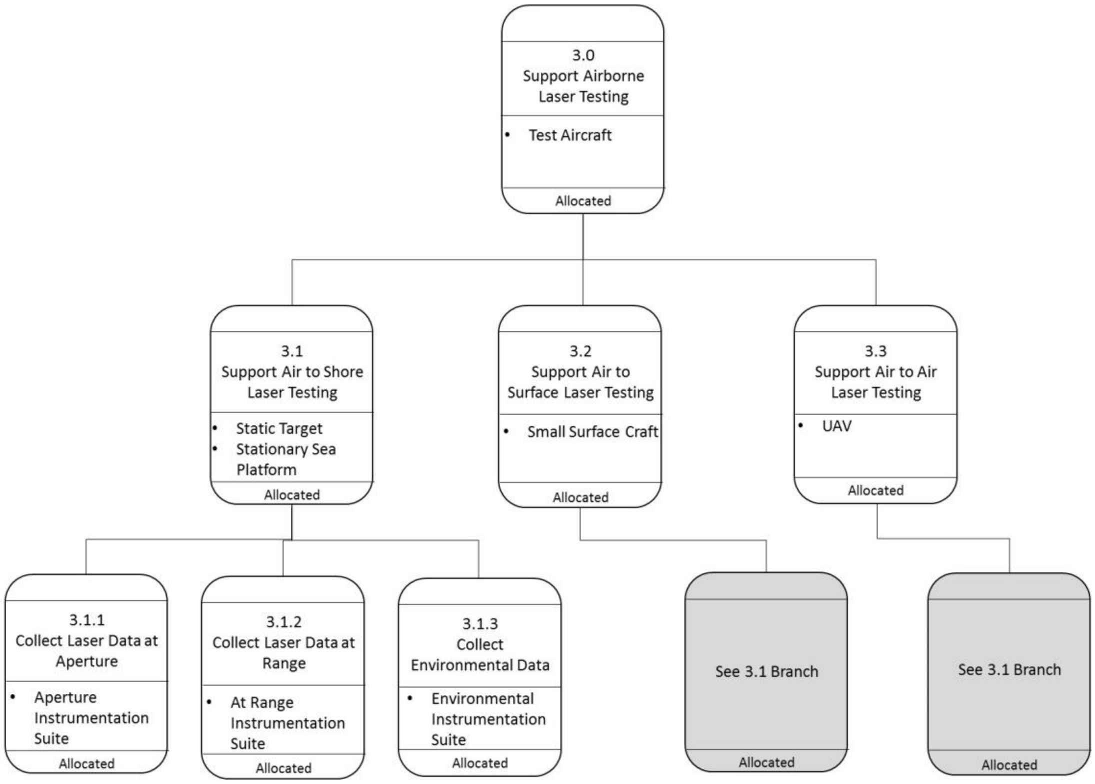


Figure 44. Airborne Laser Testing Allocated Architecture

Figure 45 begins showing the next level down in the allocated architecture, starting with laser data at aperture and the various functions and components for these measurements.

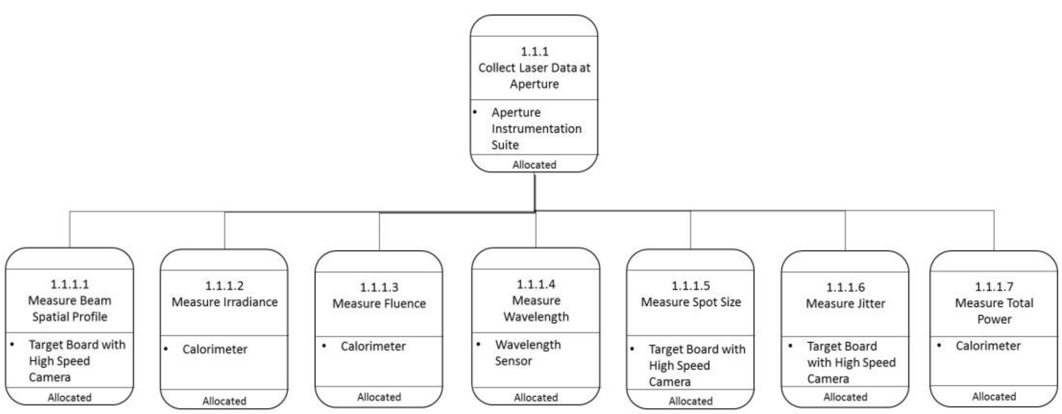


Figure 45. Laser Data At Aperture Allocated Architecture

Figure 46 displays the laser data at range portion of the allocated architecture, illustrating the types of measurements taken and the components used to take those measurements.

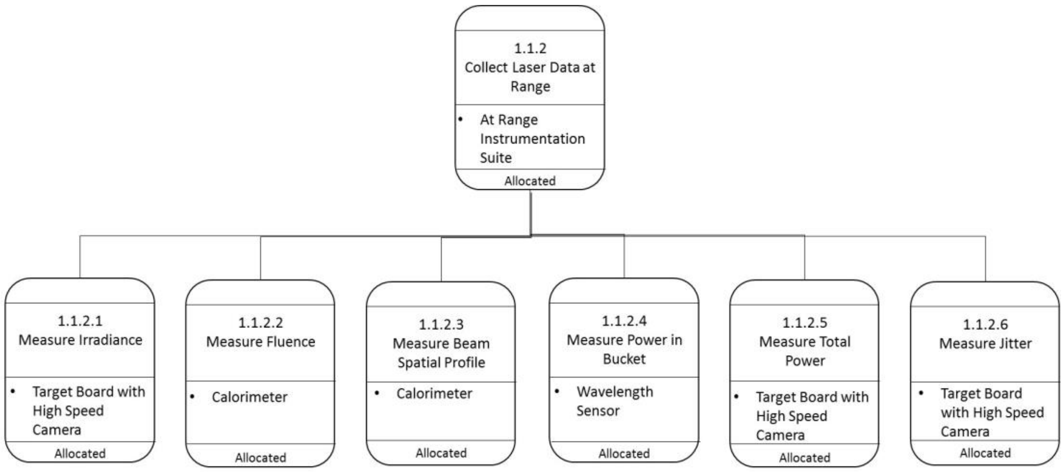


Figure 46. Laser Data At Range Allocated Architecture

Figure 47 illustrates the final section of the allocated architecture, environmental data collection. The atmospheric, meteorological, and platform measurements are shown along with the components needed to collect each measurement.

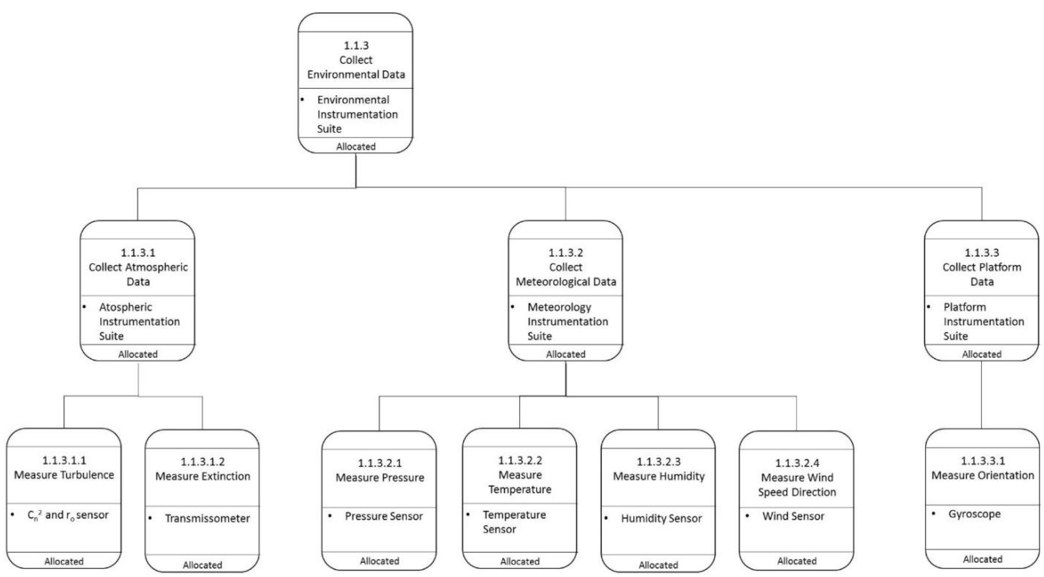


Figure 47. Environmental Data Allocated Architecture

IV. HEL TEST BED TOOLSET INTRODUCTION

The purpose of this chapter is to explore the tools required to effectively conduct test and evaluation for High Energy Laser systems. Following a Systems Engineering approach, this chapter seeks to identify candidate hardware capable of performing critical functions identified in the HEL test bed Functional Architecture. It is important to note, however, that this report is not an endorsement of one particular piece of hardware over another. Instead it is simply defining the nature of the problem being solved, describing one or more possible hardware solutions, explaining the concept of operation and physical phenomena behind said solution, and a short history of the Navy's utilization of this type of device in HEL testing.

This chapter will draw upon a vast number of sources to explore the toolset required for the test bed. Many of the devices and systems referenced herein are commercially-available solutions with a lengthy pedigree of performing the function required – such as cameras and weather equipment. Yet some other tools discussed are much more specifically tailored to High Energy Laser systems, and may be discussed in generalities to avoid issues with proprietary competition, confidentiality, and applicability. These discussions will be framed within the context of recent Navy test and evaluation of HEL systems where lessons-learned helped derive these functional and toolset requirements.

The following discussion of tools is a mapping from functional requirement to physical solutions by means of elaborating upon the devices which can execute the outlined functions. Each section is an attempt to elaborate upon certain tools available to perform measurements outlined by the test bed architecture. This is however, not an exhaustive list of every solution to each outlined function. Rather, this chapter explores several HEL-specific tools and laser-related phenomena. Furthermore, the tools discussed are not necessarily the only possible methods to conduct an HEL test, but instead are candidate pieces of hardware which could potentially be utilized in the black-box architecture.

A. ATMOSPHERIC OPTICAL TURBULENCE

Optical turbulence in the atmosphere can affect laser systems in a number of ways. The potential impacts of optical turbulence on HEL systems performance can include: fluctuations in intensity, known as scintillation; beam defocusing causing spreading of the beam, increased spot size, and reduced irradiance; and an overall loss of coherence at the target. This section includes an overview of several tools commonly used to understand atmospheric turbulence effects by measuring Fried coherence length (r_0) and the refractive index structure constant (C_n^2).

1. Overview of Physical Phenomenon of Atmospheric Optical Turbulence

As light passes through a medium such as glass or air, the light rays can be bent by a phenomenon called refraction. The degree of just how much that beam of light is deflected is called the index of refraction, and is measured relative to no bending at all – just like light propagating through empty space. The Earth's atmosphere has an index of refraction very close to that of a perfect vacuum – in fact, they are generally about 99.97% similar. However, variations in atmospheric composition, temperature, density, and pressure can change the refractive properties of the air (Owens 1967).

While these differences appear to be miniscule at first, the impact of the index of refraction is cumulative over distance. In short, the more air that light has to pass through, the more refraction it will experience. Furthermore, the entire business is made considerably more complicated by the fact that the variables involved change chaotically through the seemingly random motion of atmospheric turbulence, as discussed in the lecture titled "Atmospheric Turbulence: 'Seeing'" by Cornelis Dullemond at Heidelberg University.

The phenomenon of turbulence poses a number of unique challenges due to its complexity. To quote what is perhaps the seminal tome on fluid mechanics, "There is as yet no complete theory of the origin of turbulence…" (Landau 1987). Since turbulence in essence is the transition from orderly, uniform, predictable fluid flow towards chaotic, random flow, accurately predicting turbulent behaviors is nearly impossible in practice. Moreover, the impact of turbulence on the propagation of light and the variation of index of refraction can be seen in a commonplace occurrence: scintillation.

Scintillation, most easily observed at night while stargazing, is what causes stars to twinkle and mirages to appear blurry. Small variations in the index of refraction, distributed across countless tiny turbulent eddies, change the optical parameters in the atmosphere. These minor changes in the propagation characteristics also fluctuate many times per second (with dynamics even occurring on the scale of milliseconds), creating an ever-changing cascade of distortion. Thankfully, despite the chaotic and mutable nature of atmospheric optical turbulence effects, the large-scale behavior can be predicted stochastically. While this means that knowing the exact parameters from one millisecond to the next might be nearly impossible, it is possible to measure and even predict the bulk magnitude of turbulence and bound it within a particular range.

Ultimately, there are two ways to look at atmospheric turbulence. One common parameter measured by tools called scintillometers, is the refractive index structure constant (C_n^2). This index is a measure of the fluctuations of the intensity of incident light, which then corresponds to changes in the index of refraction along a particular path. In short, C_n^2 is a measure of what the atmosphere is doing at a particular place along that path. The other parameter, commonly used in the field of astronomy, is called *seeing* and is measured by Fried's parameter (r_0). Fried's parameter is a measure of the cumulative average of turbulence and its impact on light propagation along a particular path. Simply put, C_n^2 asks "What is the atmosphere doing in regards to optical turbulence?" and r_0 asks "How well can I see with this turbulence?"

2. How Atmospheric Optical Turbulence Impacts Laser Performance

The impact of atmospheric optical turbulence on the performance of HEL systems is several-fold. Chiefly, turbulence has two primary effects on laser systems: defocusing laser beams and introducing jitter.

Considering the effect of defocusing the beam, the turbulent atmosphere acts like an enormous collection of tiny lenses. Each turbulent eddy serves to bend light, and the large number of eddies can have a significant impact. Ultimately, this cumulative effect spatially spreads the beam of light out into a larger area. This defocusing of the beam leads to a larger spot size at the target, lower target irradiance and fluence, and necessitates longer dwell times for the required effect (Figure 54 and Figure 55).

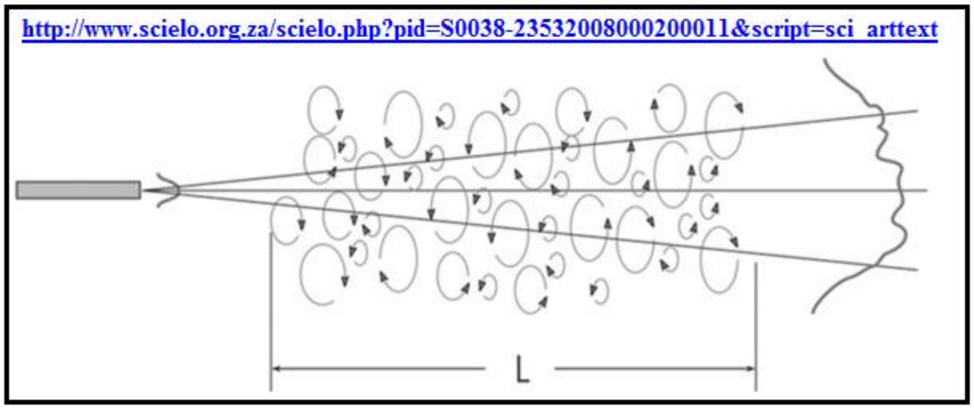


Figure 54. Beam Wander Induced by Turbulence (from Burger, Liesl, Igor A. Litvin, and Andrew Forbes 2008)

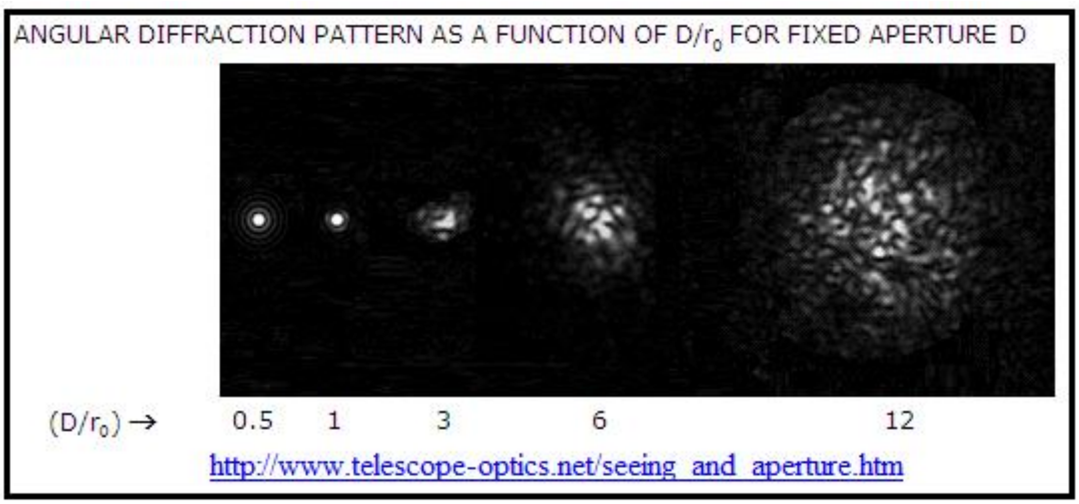


Figure 55. Effects of Increasing Levels of Atmospheric Turbulence (Lower r_0 Values) (from Sacek, Vladimir 2006)

While the defocusing impact stems from a spatial bending of the initial beam, there is also the effect of temporal variations as well. As turbulent eddies roil and roll throughout the propagation path, as vortexes damp into smaller turbulent whorls, the net refracted beam path is constantly changing. As the path changes, the beam itself wanders from point to point over time. This temporal beam wander occurs on a time scale as high as tens of hertz, and can be a significant factor in beam jitter at the target.

3. Overview of Atmospheric Optical Turbulence Tools

This section includes a brief overview of tools used to measure the effects of Atmospheric Optical Turbulence as it pertains to laser performance.

a. Differential Image Motion Monitor

A Differential Image Motion Monitor (DIMM) is a device capable of measuring Fried's Parameter (r_0) over a given path. A DIMM operates by the fact that a beam of light will wander spatially over time as it experiences turbulent effects. That amount of change is measured over time resulting in a differential measurement, and is integrated over a given time window.

The differential reading is measured as a spatial difference between two individual parallel beams of incident light. As each of the parallel beams encounters atmospheric optical turbulence effects, the directions of the beams will vary slightly – making them slightly non-parallel.

Parallel beams of light are imaged on a focal plane array or CCD imaging device attached onto the eyepiece of a simple telescope. The telescope is fitted with a mask over the aperture with two holes cut into it creating two sub-apertures. The telescope is then de-focused: this means that looking at a single object or point of light, through each of the sub-apertures, will create two distinct spots on the focal plane of the imaging device.

The two spots on the imaging device are then analyzed by a computer image processor to correspond the fluctuating difference between the spots to the turbulence distorting those incident rays of light. Through the application of several equations pertaining to optical transmission, viscous flow, and the relationship between air density and index of refraction, Fried's parameter can be calculated from merely photographing a point of light in the distance. A basic DIMM is shown in Figure 56.

http://www.maidanak.uz/telescopes.php

Figure 56. Basic DIMM Built from Off-the-Shelf Components Used for Astronomy (from Ehgamberdiev, Shuhrat 2015)

A key characteristic of a Differential Image Motion Monitor is its ability to operate and measure the impact of atmospheric turbulence in a dynamic environment.

In fact, this solution is agnostic to the particular parameters of the scenario, and can provide unbiased results through a spectrum of wavelengths and operational parameters involved in a test. In the words of Andrei Tokovinin, famed astronomer who laid the foundations for DIMM development, "Differential and absolute image motion is completely achromatic, and the response of the CCD, the stellar spectrum, etc., are irrelevant for seeing measurements" (Tokovinin 2002).

b. Scintillometers

Scintillometers observe the exact same phenomenon as a Differential Image Motion Monitor, but the way it does so is fundamentally different. Scintillometers measure the atmospheric optical turbulence by utilizing the fact that turbulence in the atmosphere has an impact on how bright or dim a light source can appear.

Atmospheric turbulence causes intensity fluctuations on the propagating electromagnetic energy. This effect is called scintillation. Scintillation is the effect which is seen when stars in the sky seem to twinkle. Scintillation is the intensity variation due to the phase distortions propagating through space from the source to the observer.

As the atmosphere fluctuates with turbulence (Figure 57), the perturbations can focus light – increasing the apparent brightness, or defocus light – decreasing apparent brightness. Similarly, these changes in focus can shift light towards or away from an observer, changing the amount of light received, and changing the apparent brightness even more. To further illustrate the phenomenon of scintillation, these apparent changes to brightness are routinely observed by the fact that stars appear to twinkle. Stars (apart from pulsars) have a relatively constant brightness, and only actually appear to twinkle due to the atmospheric turbulence distorting the incoming wavefront before it reaches an observer's eye.

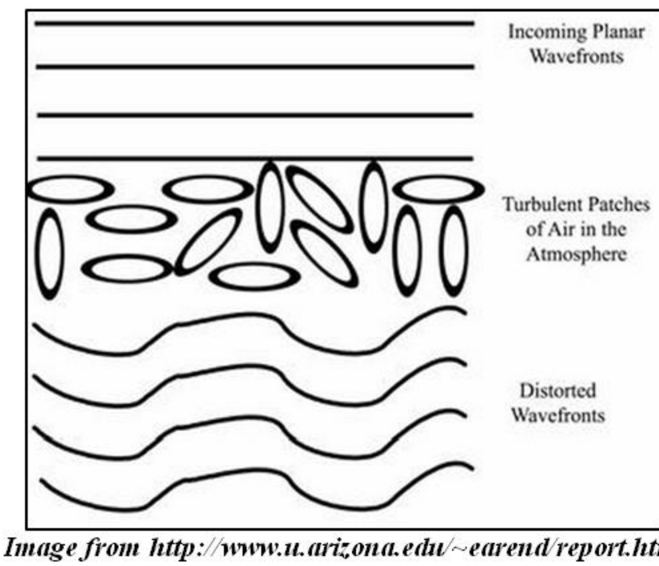


Figure 57. Wavefront Distortion caused by Turbulent Atmosphere (from Arend, Erik H. 2005)

Scintillometers rely on this phenomenon to quantify the strength of atmospheric turbulence. Looking at the average and variance of the intensity of an incoming ray of light, a scintillometer can directly measure C_n^2 - the refractive index structure constant:

$$C_n^2 = C \ln\left(1 + \frac{Var(I)}{I^2}\right) \tag{4.1}$$

Where I is the average irradiance, and C is a constant based on the physical geometry of the scintillometer.

c. Other Methods

Beyond scintillometers and differential image motion monitors, it is also possible to extrapolate how turbulence will impact a laser system through other means. Since turbulence is a function of the behavior of air, it is possible to observe the air itself and extrapolate *how* that air behavior will impact the laser. This can be accomplished with a number of tools using several different methods. One possible methodology is to employ an array of temperature sensors in the atmospheric region of interest. By mapping the temperature structure ($C_T{}^2$), it is possible to convert the temperature fluctuations (which incidentally drive the turbulence) into the refractive index structure constant ($C_n{}^2$). Additionally, there are means of measuring the vorticity of turbulent eddies by looking at the velocity profiles of air such as using anemometers, or even by listening to the sound of moving air by sensing density fluctuations with a radar-like device employing sonic detection and ranging commonly referred to as sodar.

4. Comparison of Sensors

Both DIMMs and scintillometers are used to measure the magnitude of atmospheric turbulence in a wide variety of situations – including directed energy testing. There are however, several key differences between these sensors, and understanding these differences is critical prior to effectively fielding either solution.

First and foremost, it is important to note that DIMMs and scintillometers measure two slightly different things. DIMMs measure Fried's coherence length (r_0), also known as seeing. Scintillometers measure changes in brightness to determine the refractive index structure constant (C_n^2), also known as the atmospheric turbulence strength. These two parameters are closely related as follows:

$$r_0 = \left[0.423 \left(\frac{2\pi}{\lambda} \right) 2 \int C_n^2 \left(r \right) dr \right]^{-\frac{3}{5}} \tag{4.2}$$

Where λ is the wavelength in question, and the path is integrated over the propagation path, r.

Again, as similar as these two terms are, and as convoluted as the equation would belie their relationship can be simply stated as follows:

- The refractive index structure constant C_n^2 describes the conditions present in the atmosphere.

- Fried's parameter r_0 describes how well one can see along a particular path.

Since these devices measure different things their roles in directed energy testing and the nuances of their operation can vary. One primary difference is in the weighting of the measurement along the propagation path. From how each sensor type works, scintillometers tend to weight the midpoint of the propagation path more heavily than the tails on the near-field or far-field when the transmitters and receivers have like-sized apertures. DIMMs on the other hand are most sensitive at close ranges, and they weight turbulence close to the sensor more heavily than turbulence further afield. At first blush, this difference might seem minor, but this actually means that the structure of the propagation path can yield very different results between the two devices. A common example applicable to maritime testing involves a laser under test installed on the shore near the water, with a target boat downrange in the water. In this scenario, a DIMM will measure a considerably higher amount of atmospheric turbulence than would a scintillometer. Even comparing apples-to-apples values of C_n^2 for example, after converting the measured r_0 value. The discrepancy is not something which can be overlooked either, since values can differ as much as two orders of magnitude. This phenomenon is of course due to the fact that the interface between the maritime and land environment leads to two potentially very different turbulence regimes along the path. Namely the land which is heated by solar energy heats up considerably, radiates that heat, and stirs up convective air currents. Conversely, the water in the maritime area acts as a giant heat-sink, creating a more homogenous atmosphere and lower turbulence. Since the devices have disparate weightings, they will each reflect the different conditions.

B. TRANSMISSION, SCATTERING AND ABSORPTION

This section discusses the effect that particulate in the atmosphere has on light propagating through it. The attenuation that is experienced can be due to scattering or absorption of light by these particles.

1. Overview of Physical Phenomenon of Transmission Effects

At its most basic definition, transmission is the notion of whether or not a media will allow light to pass through it, and how much that media will attenuate that light while it passes through. The determination of whether or not a material allows the transmission of light depends on its spectral absorption properties, as well as the properties of particulates in that material. In short, transmission is what light can pass through a media such that everything else either gets absorbed into or scattered off of it. For example, air with its constituent gases such as Nitrogen, Oxygen, Carbon Dioxide, is largely transparent to visible light. This is why it is possible to see through the air with human eyes. Additionally, particles and dissolved substances in the air, such as water vapor or soot, have their own properties which may differ from those of the air around it. This is of course why human beings cannot see through clouds or columns of smoke.

In its most basic definition, extinction is the measurement of how much electromagnetic energy does not propagate through a media. Extinction can be easily defined as the total of two contributing factors.

$$EXTINCTION = ABSORPTION + SCATTERING \tag{4.3}$$

Scattering can be understood as particles reflecting electromagnetic energy from their surface, without absorbing or otherwise interacting with that light. It can be broken down into three categories: Rayleigh scattering, Mie scattering, and Nonselective scattering. Rayleigh scattering is the phenomenon where very small particles reflect light. For this to occur, the particles must be comparatively smaller than the wavelength of the light – such as individual molecules. This type of scattering is what makes the sky blue. Mie scattering occurs when particles are about the same size as the light wavelength. This is commonly caused by aerosols like dust or smoke, and is what creates the reddish hues of sunsets, among other things. Finally, Nonselective scattering occurs when the particles are considerably larger than the wavelength of incident light. This tends to scatter any wavelength of light, resulting in a white opaque appearance which looks like clouds.

Spectral absorption is a characteristic tied to the subatomic properties of matter, defined by the valence electrons of an atom. Some substances will allow propagation to certain wavelengths but will scatter or absorb others. That fact means that absorption varies wildly between materials and energy levels. This means that an observer could potentially measure a very high degree of transmittance when propagating at one wavelength, but see virtually zero transmittance at others.

This characteristic of allowing transmission of some wavelengths yet blocking others is extremely important when dealing with air. In fact, while the atmosphere is quite transparent to visible light (with the notable exception of water vapor in the form of clouds), there are entire bands of electromagnetic radiation which are unable to effectively propagate through air. The most notable and applicable of these is the phenomenon known as Infrared Atmospheric Windows. Simply put, infrared light with a wavelength between around 5 and 8 microns (as well as high energy waves with wavelengths less than 100nm, such as Gamma Rays, X-Rays, and some Ultra-Violet), cannot pass through the atmosphere at those frequencies; air is opaque (Figure 58).

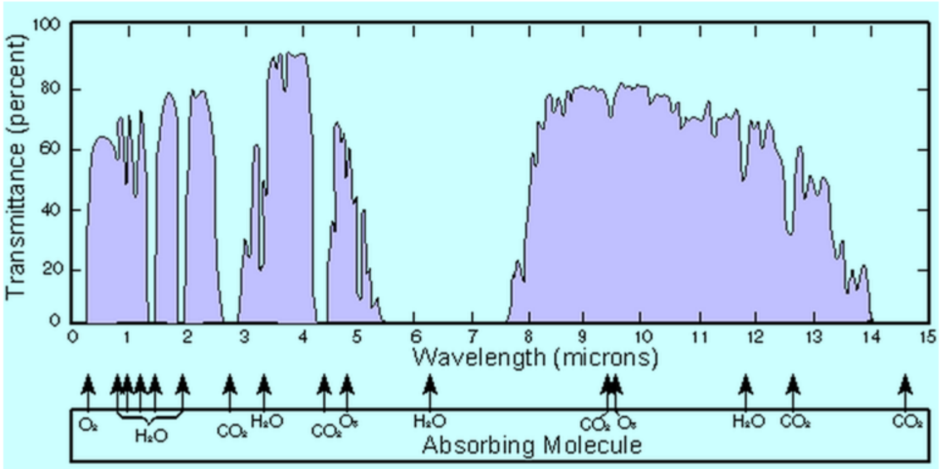


Image from http://web.archive.org/web/20010913091738/http://ewhdbks.mugu.navy.mil/EO-IR.htm#transmission

Figure 58. Transmittance of the Atmosphere in the Infrared Region (from Sticht, Doug 2015)

2. How Transmission Effects can Impact Laser Performance

Laser light must pass through the atmosphere between the laser source and the desired target. While doing so, any impediments to that transmission will have a direct impact on the light that makes it to the target. Since the effectiveness of a laser weapon system is predicated on getting a large number of photons to their destination, understanding the impediments on their journey is paramount.

This comes into play during testing when the power levels measured at the target do not match the values expected from the aperture of the laser. For instance, if a laser is expected to have a power output of 20 kilowatts, but only 10 kilowatts is measured several kilometers away at the target, it is absolutely critical to know the transmission properties of the atmosphere, and if the atmosphere is responsible for attenuation. After all, the energy from the laser could be absorbed by particulates or scattered by hydrometeors like rain drops. Otherwise, it is possible that other unrelated factors like atmospheric turbulence, non-calibrated devices, or malfunctioning hardware could be the culprit. Either way, transmission must be understood to eliminate that variable in troubleshooting a laser system during test.

3. Overview of Transmission Measurement Tools

Measuring transmission is a fairly straightforward concept in theory, although there are a number of nuances which make the practice somewhat challenging in practice. Virtually all tools capable of measuring transmission (or its counterpart extinction) employ the same fundamental physical phenomenon. Simply put: if one knows exactly how bright something is, and exactly how far away it is, one can calculate exactly how much of that light should reach a target. Measuring how much light is seen and comparing that to how much light one should see, the transmission is a simple ratio of the two.

Since light expands through three-dimensional space as it propagates, as it propagates, and that expansion is consistent and predictable, it is possible to know the radiometric intensity of light a given distance away. This phenomenon is illustrated in Figure 59.

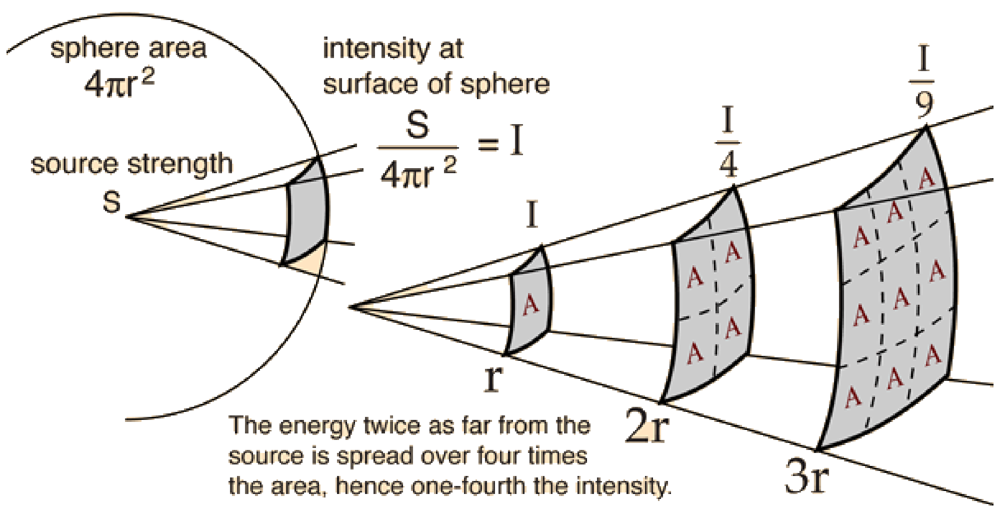


Figure 59. Inverse Square Law for Light (from Nave, Carl 2014)

a. Transmissometers

A transmissometer, also known as an extinction meter, uses the above concept of radiometry to measure how much light a sensor sees compared to how much light the sensor is expected to see in ideal transmission conditions.

All transmissometers have at least two pieces of equipment: a transmitter and a receiver. The receiver is a piece of well-calibrated equipment with a Charge-Coupled Device (CCD), photocell, imager, or other type of photon detector. This device must be calibrated to know exactly how many photons are received in a given time, which is often expressed in counts or in photons per pixel at a given brightness increment. The transmitter is a similarly well-calibrated piece of equipment, capable of emitting photons in a controlled and consistent way.

If the intensity of the transmitter is known, it is possible to know the exact distribution of photons in space, since radiation will expand following the inverse-square law. It follows then that if one knows precisely how far the receiver is from the transmitter, one can calculate the expected intensity.

This setup is comparatively easy to implement in a static controlled environment, such as at an airport (Figure 60), where the transmission parameters impact visibility among other things. There are, however, two major challenges to implanting this system in a directed energy testing role, which have been extensively demonstrated in numerous HEL test events. First, since intensity is proportional to the square of the distance from the source, knowing the distance between the transmitter and receiver is critical to ensuring an accurate measurement. This means that testing on a dynamic test range, between one or more moving targets, requires precise positioning of both ends of the system. Also, the intensity of the transmitter must be uniform, so that variations in intensity are only due to transmission effects.

Figure 60. Common Airport Transmissometer, Transmitter and Receiver (from Adshead, John 2012)

Many light sources, whether they are lasers, incandescent sources, light-emitting diodes, or even retro-reflectors, have a non-uniform intensity profile (Figure 61). Even though these sources can have a consistent intensity that does not change in time, viewing the source from a little as a fraction of a degree off-center can yield a considerably different intensity. In practice, this means that the pointing accuracy between transmitter beacon and receiver must be maintained to a considerable degree. Once again, this proves challenging in dynamic test engagements, as geometries and angles change during test.

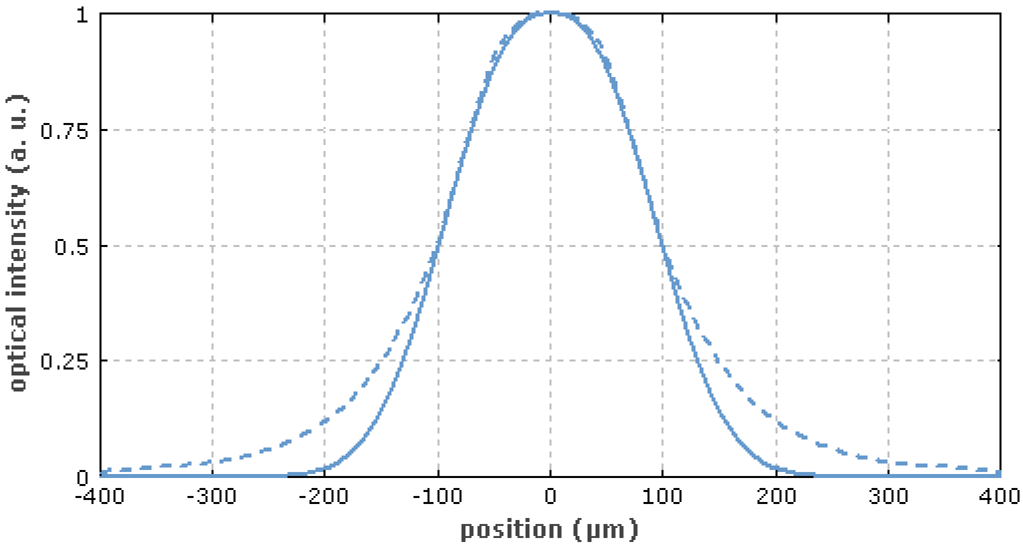


Figure 61. Common Non-Uniform Intensity Profile (from Paschotta 2008a)

b. Photometers

Photometers are a special subset of transmission sensing device, in that they pertain specifically to the visible spectrum. Of course, all light obeys the same physical laws and exhibits the same general behaviors. In practice, the only difference between visible light, infrared, ultra-violet, or any other electromagnetic radiation, is how that light interacts with other things.

A prime example of a commonly-used photometer is a sun photometer. This photometer relies on the same physical phenomenon as a standard transmissometer, but it does so with only one piece of hardware—the receiver. The role of the transmitter is played by the sun itself.

Since the sun has a reasonably constant intensity, and the earth is a relatively consistent distance away from the sun, it is possible to know exactly how bright the sun should be. The hardware of the sun photometer (Figure 62) is then simply a calibrated receiver set to track the position of the sun. Through simple geometry, the amount of atmosphere being viewed measured can be estimated through latitude and time of day, as well as sun position based on time of year.

Figure 62. Commercially Available Sun Photometer and Sun-Tracking Gimbal (from Crozel, Didier n.d.)

There are also a number of drawbacks with a sun photometer. While this transmission-measuring method is simpler to implement than a 2-part transmissometer, the challenges are twofold. Firstly, the photometer is limited to certain wavelengths, generally visible light. Different substances absorb, scatter, or otherwise attenuate light to varying degrees, depending on wavelength, so atmospheric behavior could potentially be different from the wavelength of interest to the weapon system. Also, the propagation path is obviously limited to the line towards the sun. While this path could be used as an approximation of transmission characteristics of interest to a test asset, it will only ever be an approximation. Understanding the transmission parameters experienced by the beam itself requires a measurement along that beam to be completely accurate.

4. Comparison of Sensors

Both types of sensors described above can be utilized by the Directed Energy test bed, each with relative strengths and weaknesses. Since sun photometers are limited to slant-path measurements between a fixed ground location and the position of the sun in the sky, this device has a role in particular slant-path engagements, such as Surface to Air or Air to Surface engagements. These solutions are fairly trivial to install, straightforward to calibrate, and are commercially available to easy integration into the test scenario.

Of course, with the defined limitations of the photometers, transmissometers of one sort or another will be required for DE testing. Since a transmissometer setup, complete with calibrated receiver and transmitter can be positioned dynamically throughout the test range, it will be possible to take measurements exactly when and where the test scenario dictates. By measuring along the propagation path of interest, this will ensure that any effects such as aerosol particulates, fog, and moisture are measured. Care must be taken to accommodate the challenges imposed by the two-part transmissometer setup; namely, the precise pointing and positioning of components. Ultimately, this solution or something like it, will be required to completely understand the nature of transmission in the atmosphere on the test range.

C. IRRADIANCE AND FLUENCE

This section discusses irradiance and the different tools that are available to measure it. With advancing power levels, due to developments in solid state laser technology, the tools have to evolve just as rapidly.

1. Overview of Physical Phenomena of Irradiance and Fluence

One of the most critical parameters to measure when evaluating a HEL system is how much energy is being delivered and at what rate for a given target area. Lasers operate by emitting a beam of photons which propagate towards a target, where it transfers energy in the form of light and heat. To quantify those terms, it is useful to measure fluence and irradiance. These terms are defined by the energy per unit area, or the power per unit area, respectively. Fluence is often represented in units of joules per square centimeter, while irradiance is often represented in units of watts per square centimeter.

It is also important to note that these two terms are closely related. Power, measured in watts, can be understood as joules per second—or that power is how fast energy is delivered. Therefore, the relationship between irradiance and fluence is that fluence can be understood as the irradiance measured over a finite time interval.

2. Importance of Irradiance and Fluence Measurements on HEL Testing

Knowing the irradiance and fluence of a given laser system is central to understanding a wide range of other characteristics of the unit under test. It can be compared against output power to understand the jitter of the laser, tracking system, mount, and pointing system and can also be extended to include atmospheric jitter impacts. Irradiance and fluence also form the basis for evaluating lethality since material failure criteria is often defined by threshold energy and power for a given material area.

There are two primary types of measurements which are important to consider pertaining to irradiance and fluence, and their implications determine the types of equipment required to make these measurements. These two categories are defined by the location at which the measurement is taken: whether at the aperture of the laser system or downrange at the target itself.

Collecting measurements of irradiance and fluence at the aperture of the laser is perhaps one of the most fundamental measurements which can be taken during an evaluation of a HEL system. By measuring the energy and power intensity at the aperture, it is possible to know exactly how well the system itself is performing, without the added impacts of weather, target interactions, or atmospheric conditions. There is also the added benefit of being able to bring larger and more complex tools to bear for readings at the aperture. HEL systems tend to be fairly large, often requiring land resources or Navy ship integration to operate. It is, therefore, likely that there will be ample room near the laser to install and operate any applicable irradiance and fluence sensors of varying size, weight, and complexity.

Irradiance and fluence at the target introduces potentially more information than a simple reading at the aperture; although, taking such a reading can introduce several other challenges. By collecting these values at the target itself, one can see the actual effects of the environment including that on the laser system, the atmosphere it is shooting through (including atmospheric-induced jitter), the properties of the target, as well as any ancillary equipment which might contribute factors such as tracker jitter and base motion. As such, this provides the most realistic illustration of how the system is performing in a realistic operational environment.

Collecting readings at the target itself can be considerably more challenging than obtaining one at the aperture of the system due to the additional parameters to consider. In many testing scenarios, the engagement geometry might vary with time, since targets might move. This means that any tool required to collect irradiance and fluence data at a target must be capable of moving with the target. In the case of a HEL employed against an aircraft or small boat target, weight constraints might further limit the types of tools available to do the job. Finally, measurements taken at the target must also be done with sensors that have sufficient survivability or low enough cost that if the target were to be destroyed during the test, the tool could be reused or replaced to promote fiscal responsibility.

3. Overview of Irradiance and Fluence Measuring Tools

There are several types of tools which can be used to measure irradiance and fluence depending on the scenarios in which they are used. Based on their employment, the methods of action for these devices can vary considerably. This section compares and contrasts the tools in their respective roles.

a. Flat Plate Target Boards, Ablatives, and Acrylite

Arguably, the simplest way to measure irradiance and fluence is to place a piece of material in the path of the beam and see what happens. This method of using a target board or target coupon is based on the fact that a change in a given material will occur after the material has absorbed a certain amount of energy within a certain time. Plastics and metals can melt after they have received a particular amount of energy, and some materials will evaporate or ablate after they absorb so much heat. One of the most commonly used materials for such a test is a type of acrylic sheet called Acrylite. Acrylite is a light weight plastic which has a constant rate of energy absorption, and it melts at a consistent point after absorbing a certain amount of photons. Therefore, a laser system can be engaged for a given amount of time, emit photons towards an Acrylite plate, melt a given mass of the material, then be switched off; the amount of melted material can be equated to the total irradiance and fluence of the laser at the point of measurement.

The way this change can be measured could be explained with the following example: a piece of aluminum will melt if it absorbs approximately 321,000 joules of energy per kilogram of material. Based on the density and the thickness of the piece of aluminum, one can determine how large of an area corresponds to each kilogram of metal. If a laser is capable of melting a hole of a certain area, one can derive how many joules of energy were absorbed in that area; energy per area (joules per square centimeter for example) is fluence. Dividing the measured fluence by the time required to obtain such results yields the average irradiance experienced during the duration.

Figure 63. Sample Acrylite Material with Laser Burn Area (from Ophir Optronics 2015)

One of the largest benefits of this method of measuring irradiance and fluence is that the solution is cheap, simple, and repeatable. A piece of material can be installed on any type of target, without any additional sensors, batteries, onboard computers, or electronics. The material plate method is virtually fail-safe since it requires no power, has no moving parts to fatigue and fail, and can be inspected and replaced as needed. Additionally, the material can be calibrated relatively easily to understand the relationship between melting rates, incident energy, and power. Further, this calibration will remain valid as long as this type of material is used.

However, this solution is not without its downsides. It is important to note that once an Acrylite plate melts, an ablative burns off, or a target material undergoes some physical change—that material can no longer be used again. Granted, this simple target board method is comparatively inexpensive versus high-tech sensors. However, the fact that the board is one-time-use introduces challenges of its own. Particularly, if the plate is installed on an unmanned vehicle like a small boat or UAV, that vehicle would have to return to a staging area to uninstall the melted plate and reinstall a fresh one. In many testing scenarios, this delay between test runs can incur a considerable cost since airspace restrictions and range clearance can be a valuable commodity.

Additionally, using a target plate is not a blanket solution either. Materials have a certain threshold where readings will be valid. For instance, a one-watt per square-centimeter laser shined for one thousand seconds will measure just as much fluence as a one-thousand-watt per square-centimeter laser operated for one second. However, despite having the same fluence, a material like Acrylite or metal may not respond to the lower irradiance case since passive effects like convective cooling, radiative heat, or ablated material could lower the surface temperature. Ultimately, this means that a target board material must be specifically chosen for the engagement power level, irradiance, and fluence. Further, some scenarios will not be suitable altogether.

b. Photon-Counting Sensors

Sensors exist which count the incident photons over a given test area. These devices observe the brightness of light which hits a sensor similar to how a digital camera measures photons encountering its Charge-Coupled Detector (CCD) mechanism. The intensity of light energy, measured in watts of power can be directly observed by such a device. Additionally, the device has a certain area it is able to measure. Therefore, by knowing the incident power and the observed area, photon-counting sensors can indirectly measure irradiance.

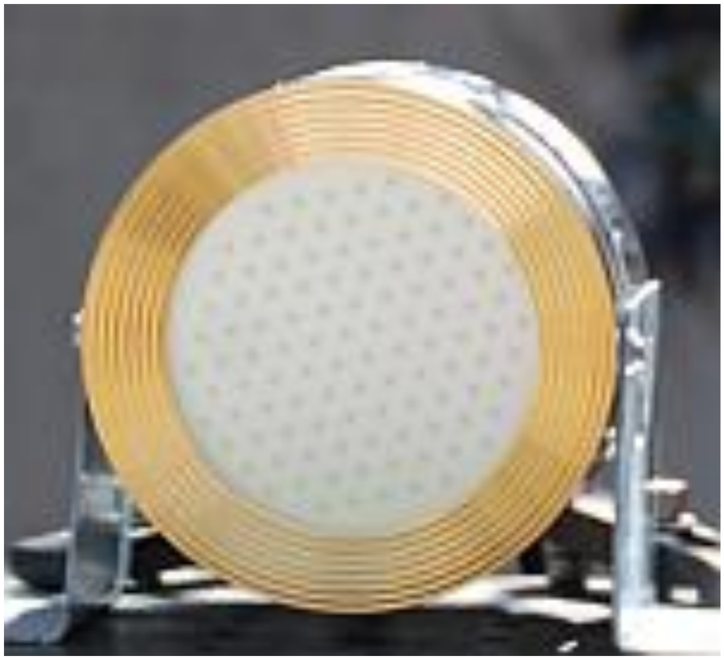


Figure 64. Commercially Available Photon-Counting Irradiance Sensor (from SemQuest 2015)

Photon-counting sensors have a strong benefit over target board style methods in that they are electronic and can store multiple trial runs in an onboard data-logger computer. This means that a single sensor can be outfitted onboard a target vehicle or target location, then that target can be fired upon over and over again. As long as careful planning is employed to not damage the sensor, it will collect data over a number of test runs, thereby saving range time and ultimately money.

One key drawback of an optical photon-counting sensor is the fact that the sensor will often be limited to a fairly small area. These devices generally use silicon wafer technology which is inherently limited by the manufacturing capability of semiconductor fabrication. As such, it is not uncommon for a given laser beam spot to "overspill" the sensor. The sensor is only able to measure incoming light that it is able to see, and any laser light that misses the sensor will not be observed or measured. Depending on the range of the engagement measurement and the spreading introduced by atmospheric turbulence aberrations, this limitation can be potentially damning. This drawback becomes particularly egregious when a test team wishes to measure the lobes of a laser spot further away from the center hot-spot. Since a laser's spot size is governed by the airy function, these patterns hypothetically extend out towards infinity. While it is never practicable to measure an infinitely large object, it is sometimes necessary to understand a certain portion of it.

Still, this drawback can be mitigated. Properly designing the experiment in question can ensure that the region of interest (including tails, wings, and lobes) is sufficiently within the sensor area. This can be done by collecting data at shorter ranges thereby limiting the amount of beam spread, decreasing the laser spot size, and increasing the measured irradiance in that area.

c. Thermal Loading Sensors

Thermal loading sensors measure the interaction of incident laser light on a calibrated material by observing temperature changes from the absorption of energy. This method used to measure irradiance and fluence, based on the principle of calorimetry, is perhaps the oldest and most commonly used in a wide variety of applications, even beyond that of HEL testing.

Thermal loading sensors are essentially a hybrid solution, embodying fundamental elements of both target board and photon counting irradiance and fluence sensors. Similar to flat plate target boards, thermal-based sensors employ a certain type of material and observe how it responds to being hit with laser light. Rather than melting or ablating however, these thermal sensors simply heat up in a consistent and calibrated fashion. The change in temperature therefore is proportional to how much energy is absorbed over a given sensor area. It is defined as follows:

$$\text{fluence} = \frac{(\text{sensor heat capacity})(\text{change in temperature})}{(\text{sensor area})} \tag{4.4}$$

These thermal sensors are also similar to photon-counting sensors in that they are able to be used multiple times and are not destroyed by collecting a measurement. The devices use an electronic sensor to measure the change in temperature, such as a thermistor or thermocouple, which transduces the change in temperature into an electric signal. Like photon-based sensors, these devices can be equipped and calibrated once on a target vehicle or location and used for multiple test runs.

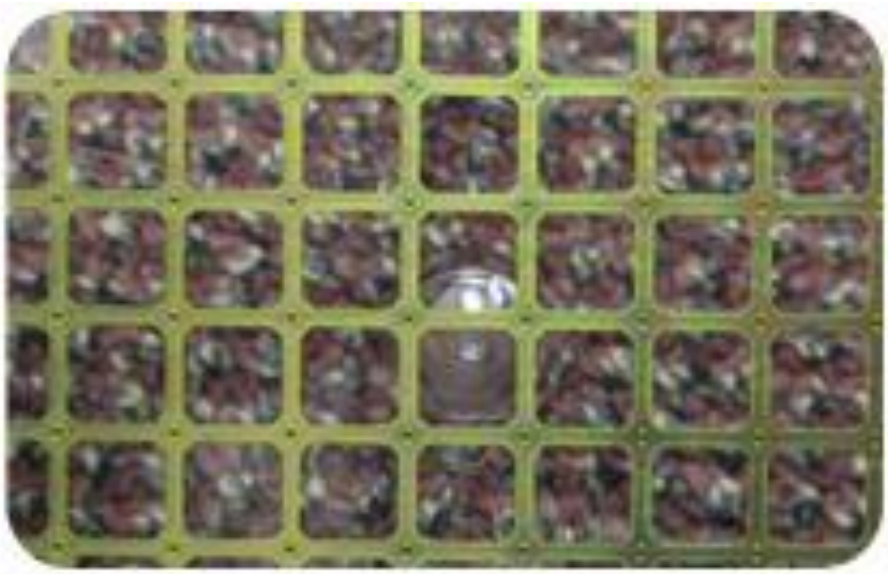


Figure 65. Commercially Available Thermal Loading Irradiance Sensor (from Aegis Technologies 2010)

Once again, thermal sensors are not a cure-all solution to conducting irradiance and fluence measurements. There are two key limitations. First is the factor of weight. In order to be able to handle the intensity and power levels associated with a HEL system, thermal sensors need to have considerable thermal mass or integrated cooling systems. This implies that these thermal devices can be large, heavy, and bulky which might preclude their use on aircraft, small boats, or other load constrained targets. Another considerable factor to understand is that of transience and response time. Similar to the minimums of Acrylite target boards and the maximums of the photonic sensors, these thermal sensors have a minimum and maximum irradiance and fluence ranges for which they are valid. Beyond potentially damaging the sensor, there is a non-trivial time delay involved in heating the sensor; from the time the laser is switched on, to the time the temperature of the target appreciably increases, to the time the sensor recognizes it, there is a delay. This delay is further muddled when one considers external factors which could contribute, such as cooling effects of airflow on an aircraft target or splashes of cold water on a boat target, to name a few.

4. Summary and Comparison of Sensors

Each of the systems has their relative strengths and weaknesses, which must be assessed on a case-by-case basis. Depending on the type of engagement being studied—whether taking readings at the aperture of the laser or afield onboard some type of target—technical tradeoffs among sensor solutions must be considered. Additionally, constraints imposed by cost, scheduling, and repeatability can influence a test planner in determining which of these solutions is appropriate for which engagement. Finally, physical constraints of the test setup must be considered. Heavier but cheaper sensors could be ideal for targets on land, while expensive lightweight options would need to be considered for aircraft targets with limited payload capacity. Ultimately, these tools are all useful within the realm of the HEL test bed, and test coordinators must tactfully employ the appropriate tools to meet their objectives both effectively and efficiently.

D. SPOT SIZE

Spot size is an essential parameter when evaluating laser performance. This section describes the information found within the beam spot at range as it can be affected by the atmosphere, diffraction, and jitter.

1. Overview of Physical Phenomena of Spot Size

In order to really determine the quality of the laser beam that is being emitted, it is important to examine the beam width (spot size). It is known that laser output beams closely approximate Gaussian beams, and the intensity distribution is dependent on the beam width. Beam width plays a very important factor on the intensity distribution of the laser beam output because it encompasses 86.5% of the beam power (Smith 2008, 196). The beam width for a Gaussian beam spreads out based on the following relationship:

$$w_z^2 = w_0^2\left[1+\left(\frac{\lambda z}{\pi w_0^2}\right)\right] \tag{4.5}$$

This is the rate at which the beam spreads out as it gets farther away from the beam waist—the narrowest part of the beam—at a certain distance, z, along the beam axis. As the distance from the beam center increases (i.e., closer to the edges of the beam), the intensity of the beam will decrease. The distance from the central axis of the laser output beam to the edge of the beam is known as the beam divergence; the larger the divergence of the beam, the lower the intensity of the overall beam will be, and thus, lower beam quality. As the laser light propagates farther away from the source, the beam will diverge, causing some wave front curvature. This curvature increases with the distance away from the beam waist according to the following relationship (Perramet al. 2010, 112–113).

$$R_c(z) = z\left[1+\left(\frac{\pi n w_0}{\lambda z}\right)^2\right] \tag{4.6}$$

At the beam waist, the wave front is planar, which leads to a diffraction limited beam. As the distance from the beam waist increases, the spot size linearly increases as well. This is illustrated in Figure 66 and described by the divergence angle, as described below.

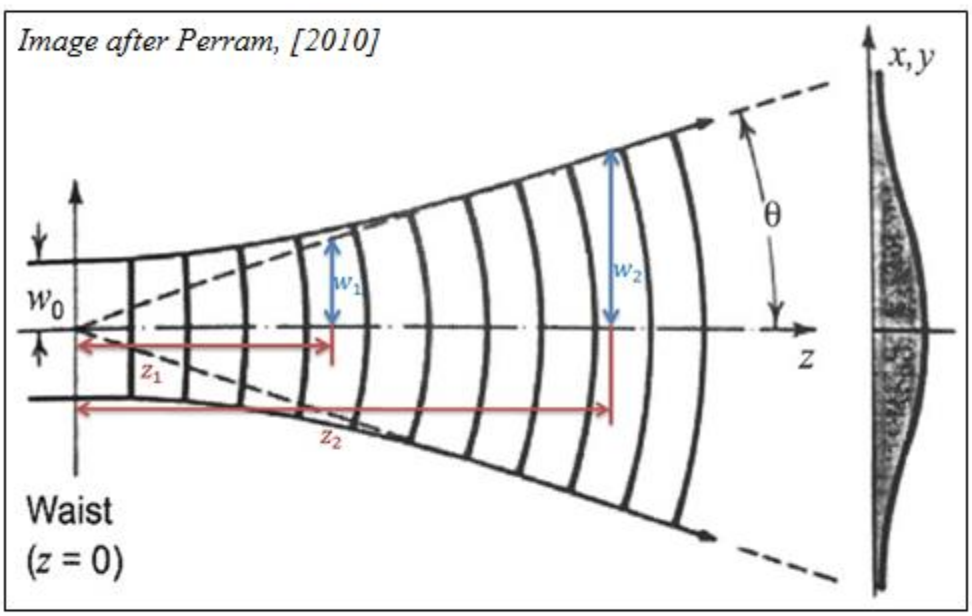


Figure 66. Laser Beam Divergence (from Perram et al. 2010)

In order to calculate the laser beam divergence, the beam radius must be measured at two different distances along the output beam axis. If beam radius w_1 and w_2 are known at two different distances (z_1 and z_2) along the laser output beam, then the divergence angle is described as follows (Perram et al. 2010, 113).

$$\theta_{½} = \frac{dw}{dz} = \frac{\lambda}{\pi n w_0} \tag{4.7}$$

Divergence effects will be more noticeable in a maritime environment closer to the surface of the ocean, due to additional beam scatter, absorption, and turbulence effects. In order to keep the divergence low for a laser output beam, it is required to have a larger beam diameter.

2. How Spot Size Relates to Laser Performance

In order to measure laser beam quality, one must look at the Beam Parameter Product (BPP), which is the product of the laser beam's divergence and the (semi) diameter at the waist. Since the BPP is dependent on the wavelength of the laser, the ratio of the BPP for an actual laser beam and that of an ideal Gaussian beam at the same wavelength is used to determine the beam quality factor, or M^2, which is independent of wavelength.

Although the beam quality factor is a good way to quantify laser beam quality, it is a difficult parameter to measure, and for that reason, cannot be relied on solely. In order to acquire an M^2 valued for a laser output beam, one must measure the beam width at various different locations along the beam. Per ISO Standard 11146, the minimum amount of points that are required to be measured is ten. Once these points have been collected, they are plotted as beam radius vs. position, as shown in Figure 67.

Image from Paschotta [2008]

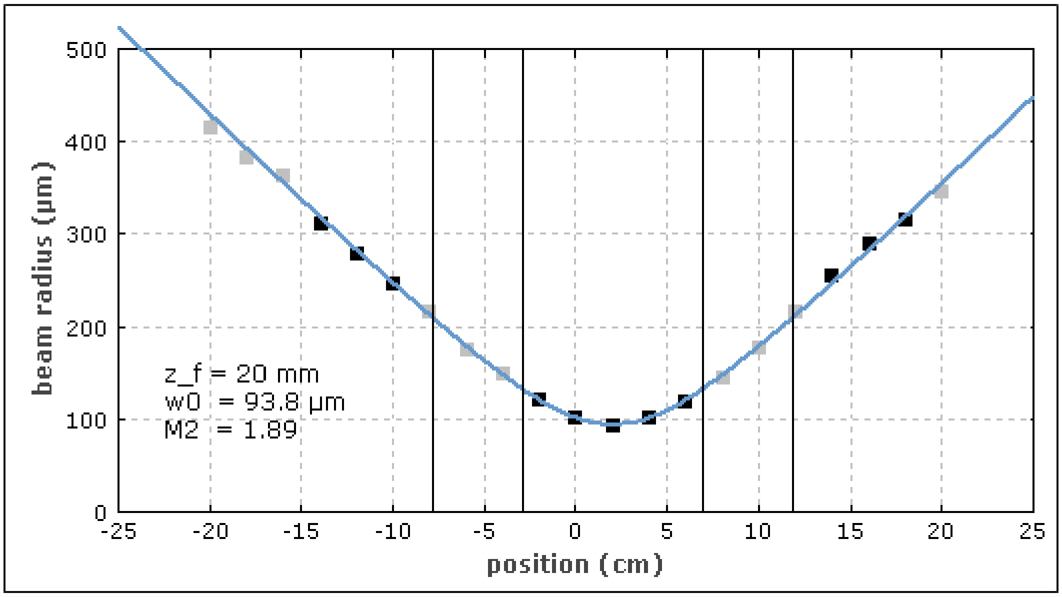


Figure 67. Beam Radius vs. Position (from Paschotta 2008b)

One difficulty that has been observed in this process is that the laser must be perfectly aligned. If not, the sensor measuring the laser beam width may not capture the most accurate data, and thus result in an erroneous M^2 value. There are various detectors that will allow for a quick way of measuring beam diameter at various lengths along the beam. For example, slide rail detectors are common in the modern day; however, these methods work reliably only under a controlled, laboratory environment. In the case of HEL testing it would be very difficult to accurately measure the spot size of the laser output beam at various distances along the beam path. Another challenge with correctly measuring the beam radius is the fact that ambient light will affect the sensor reading. In other words, the intensity captured by a sensor may not be truly representative of the laser output beam, but rather also factors in ambient light. This will be a particular challenge for the HEL test bed because the effects of sun glint when attempting to measure the laser output beam will definitely play a role. One of the most common ways to mitigate this factor is to use narrow line filters on all optics involved. Since lasers emit light at a narrow band, it is possible to use this method to filter out a significant portion of extraneous light—up to several orders of magnitude.

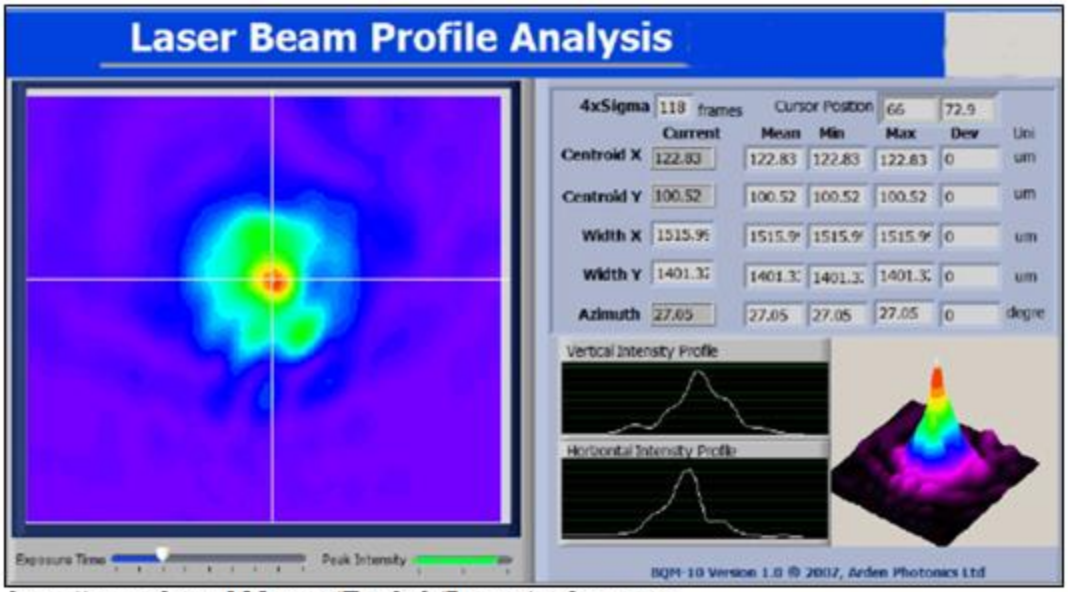
As a result of the behavior of a Gaussian beam, the beam will diverge much faster if the spot size is smaller. This means that although the laser has a high power output, it will not provide a high enough intensity due to beam divergence and the inability to focus on a spot enough to provide a lethal amount of energy on a target. One way to increase the beam diameter is explored in the paper "Free Electron and Solid State Lasers Development for Naval Directed Energy." In order to increase the beam diameter, while leaving a small optical mode waist in the center (to resemble a Gaussian fundamental mode as closely as possible), a short Rayleigh undulator is required (Kalfoutzos 2002, 65). By having a short Rayleigh length, the spot size of the beam will be large enough to keep divergence low, and the power intensity that is produced will not cause any damage to the cavity mirrors.

3. Overview of Spot Size Measurement Tools

This section provides a brief overview of the tools and methods for measuring spot size for HEL systems.

a. Scanning Aperture Approach

The scanning aperture approach is comprised of two different techniques that accomplish the same thing. The first one uses a knife-edge that cuts through the laser output beam, and the transmitted power is then measured. A plot of the measured beam intensity and knife position will yield a curve that is representative of the integrated beam intensity in a single direction. By knowing the intensity of the curve in several directions, the original beam profile can be recreated. Essentially, the laser beam profile is sliced at various angles and tomography algorithms are used to generate an energy distribution plot. The second technique uses a narrow slit instead of a knife edge to dissect the laser output beam. Using this approach, the beam intensity is integrated over the slit width, rather than plotted against knife position.



http://www.laser988.com/English/BeamAnalyser.asp

Figure 68. Laser Beam Profile Analysis (from Zhang, Grace)

Although these measurement techniques can provide an accurate measurement of spot size, there are some drawbacks. For one, they do not offer a continuous readout, which can lead to some degree of measurement error and provide a slightly erroneous beam profile depiction. Secondly, they do not provide an actual two dimensional spatial profile, but rather provide the integrated intensities in the x and y directions separately. This can lead to misinterpreting of the laser beam intensities when it comes to very complex beam profiles.

As described before, either scanning aperture approach yields beam intensity measurements that are then used to recreate the output beam profile. A photodetector will record the laser beam intensity as it passes by the knife edge or through narrow slits on the slit profiler, Figure 69. The photodetector takes beam samples in the x and y directions and this information is then fed into software to provide an accurate beam profile. This analysis will provide several features of the laser beam’s characteristics, such as beam diameter (spot size), three dimensional profile, and power distribution information.

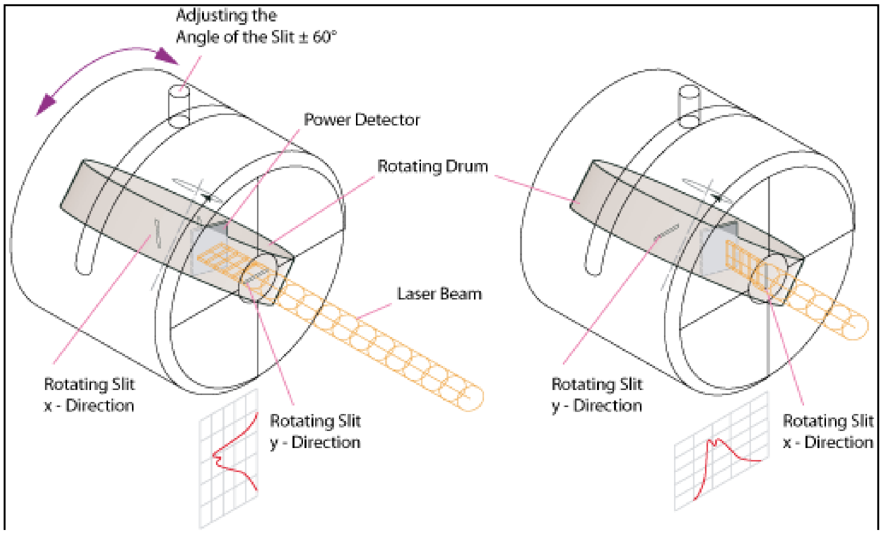


Figure 69. Scanning Aperture Technique Overview (From Thorlabs 2015)

b. Cameras

Beam diameter can be defined in multiple ways and can be distinguished within the context of HEL weapons: the D86 width. This definition is used because it is crucial to know how much power is being delivered to a target. The D86 beam diameter is calculated by determining the area around the centroid of the beam profile that contains 86% of the total beam power. This percentage is used because, for a Gaussian beam, 86.5% of its total power is located within that specified beam diameter (Smith 2008).

Another approach used in measuring laser beam profile (and in turn the D86 width beam diameter), makes use of Charge-Coupled Device (CCD) cameras. Using a CCD camera to measure beam profile has several advantages, such as capturing profile in real time, providing beam profile characteristics in real time, and continuous measurement. The CCD is usually connected to a PC interface that directly measures laser beam profile and provides the laser intensity distribution plot.

The process of using a CCD camera to measure the laser beam profile is to attenuate the laser beam onto a CCD. Since the beam width can be heavily dependent on the outer tail of the laser profile provided by the laser profiler, it is essential that the pixel values on the edge of the image are subtracted from the measured intensity. If this is not done, the beam width value provided will be much larger than it should be. In order to determine what these baseline values are, one must first measure the amount of pixels recorded by the CCD with no laser light coming into it. After these values are noted, the laser light can then be accurately measured.

4. Comparison of Techniques

Both the scanning aperture technique and the camera approach provide information on the overall laser output beam profile. The information provided by either of these techniques includes, but is not limited to, beam width. Although both of these measurement techniques yield the same information, CCDs are more widely used, due to their ease of use and ability to provide real time data.

For a HEL test bed in a maritime environment, it would probably be best to use the camera approach. This will allow the laser beam profile to be measured directly, and will provide the most accurate information because it will be real time data. With all other factors involved in HEL testing, the camera approach is preferred for those conducting the testing allowing for more accurate and direct data.

E. JITTER

Jitter plays a significant role in determining laser weapon system performance. This section describes the effects jitter has on total power on the target as well as jitter's effect on performance.

1. Overview of Physical Phenomena of Jitter

Weapon systems that employ a stabilized pedestal and tracking system for acquiring and engaging a target have to mitigate the contributions of their environment against their ability to maintain sight of their target with high accuracy. There are a number of factors that contribute to a HEL system's ability to maintain a position on target at range. Some of these factors include: atmospheric influence, tracking algorithm induced errors, platform motion, and laser induced vibrations. A weapon system, HEL or not, must mitigate the contribution of this motion in order to be effective. The level of correction needed is dependent on the system being employed, the target being tracked, and everything in between. A Naval weapon system deployed on a destroyer class ship for instance, must compensate for motion the ship is experiencing due to the sea state as well as the inherent vibrations generated by the power plant, rotor shafts, gimbal gears, etc.

These disturbances cause the laser weapon to experience what is known as jitter. Jitter is defined as "motion of the centroid of irradiance of a laser beam spot relative to a reference" (Perram et al. 2010). Jitter also refers to the motion of the HEL far-field spot about the aim-point. Jitter is commonly described using an angle (θ) which for stabilized systems can be in the range of microradians. The equation below is used to calculate peak irradiance while accounting for beam spreading caused by diffraction, jitter and atmospheric tilt.

$$I_{PJ} = \frac{P}{2\pi\left(\sigma_d^2 + \sigma_j^2 + \sigma_t^2\right)} \tag{4.8}$$

The elements that compose the denominator represent variances for diffraction, jitter and atmospheric tilt, respectively. In this equation, a Gaussian approximation has been used to simplify the summation of the individual variances.

For laser weapon systems, this jitter is overcome with Fast Steering Mirrors (FSMs): isolation at the known frequencies or inertial reference units, for instance. There are limitations with each method. Employing one or more of these and other mitigations such as improved tracking algorithms could potentially increase the system's lethality by several orders of magnitude. According to Harney:

> If λ/D is much less than 1 mrad, aimpoint jitter due to platform vibrations may significantly move the beam around its long-term average centroid on millisecond time scales and smear out the energy deposition. One function of the beam pointing system in high energy laser weapons is to provide inertial stabilization of the beam. This can reduce jitter effects to acceptably small levels. (Harney 2013)

The laser beam is not the only component affected by vibrations within the weapon system. Optical instrumentation used for acquisition and tracking are affected in the same way. Depending on the severity of the fluctuations, smearing can take place across the tracking image sensor. Jitter is very detrimental to the overall system performance and there are continual efforts to reduce its effect on laser weapon systems.

2. How Jitter Relates to Laser Performance

Laser weapon performance is heavily dependent on the system's ability to mitigate the jitter experienced during operation. Jitter reduces the intensity of the beam causing the warfighter to have to engage a target longer than desired. For example, a 100 mm diameter laser beam with 10 µrad of jitter will result in roughly a 400 fold decrease in the intensity of the beam at 100 km due to the jitter alone (Watkins 2004). With kinetic weapons, when a projectile impacts its target, it may not hit the intended aimpoint, but significant damage is done to the target. For laser weapons, if the systems cannot maintain the intended aimpoint, within a smaller degree of error, it may never reach the damage threshold of the material.

To damage a target in the operational environment, is in itself, a challenge. When the range of engagement is increased, these challenges are exacerbated. From a design standpoint, the total power achieved by the laser weapon versus the ability to reduce the jitter to an acceptable level is a constant decision point for most programs. This is due to the fact that one will never be able to reduce the total jitter to zero and designers will desire more power. The decision of power versus jitter is illustrated in Figure 70.

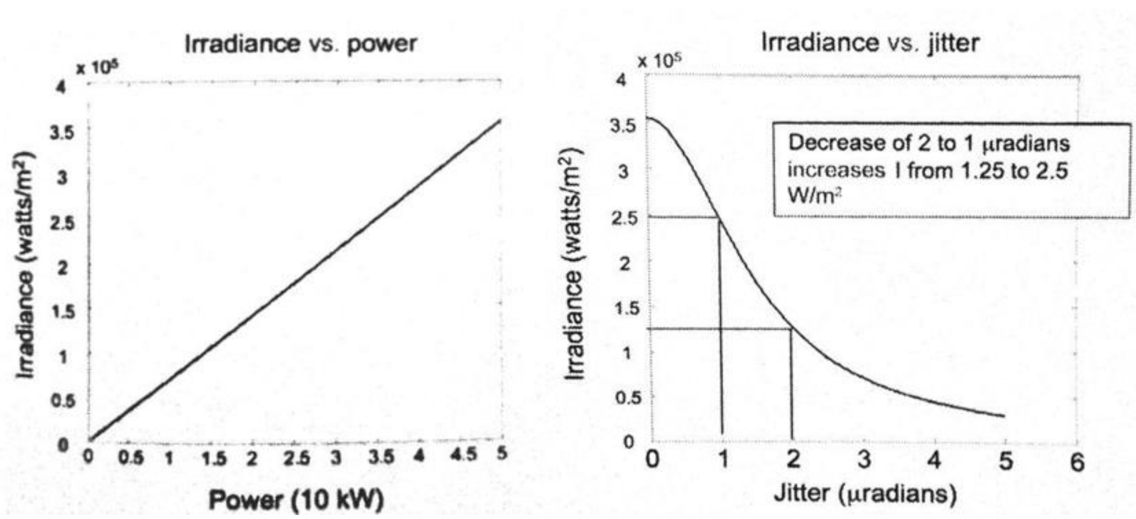


Figure 70. Power vs. Jitter Trade-off (from Nielsen 1994)

Figure 70 compares the trade-off between increasing power and reducing beam jitter. The system starts with 2 µrad of jitter and 1.25 W/m^2 of power on target (Perram et al. 2010). In the left image, the power is doubled from 1.25 to 2.5 W/m^2. On the right, jitter is reduced by half improving the irradiance to 2.5 W/m^2, the same result as increasing the power. System stakeholders can then use this comparison to conduct appropriate trade-space studies to determine the most cost effective path forward in laser design.

Jitter is generated by various sources and not strictly from the laser or weapon system itself. For example, the atmosphere can induce a tilt in the wavefront causing image motion over the track camera which is known as atmospheric jitter.

Figure 71 depicts energy being deposited on an imaging focal plane after travelling through the atmosphere. The incoming wavefront represents the energy transmitting through the environment without turbulence while the tilted wavefront has been exposed to atmospheric turbulence. Atmospheric characterization instrumentation measure this effect due to turbulence using a method similar to the one described above. Per Figure 71, the energy is deposited on a different location after passing through some level of turbulence which has spread the energy over a larger area which is unintended. How large of an area the energy is spread over is dependent on many factors which were covered earlier in Chapter IV. The way the energy is spread across the imager focal plane is the same type of distribution of energy that will occur when a laser propagates though the atmosphere. The size of the cells that create this turbulence contributes to how frequent the changes in wavefront tilt happen and how much the beam will spread. As shown, the peak irradiance is reduced over time due to the distribution of power. This means that the laser will have to engage the target for a longer duration to achieve the same effect.

Figure 71. Wavefront Tilt Effects on Imager (from Teare, Scott W., and Sergio R. Restiano 2006)

The origin of jitter within a system is fairly easy to locate, and there are a number of methods to mitigate this effect. The test bed is required to measure the total jitter from the systems under test at ranges in the tens of kilometers, which it not as trivial. There are limitations with respect to payload capacities for some of the scenarios described in Chapter II along with sensor limitations. The tools described below are the most feasible for capturing this data in a dynamic operational setting. These sections provide a brief overview of the tools and methods for measuring jitter for HEL systems.

3. Overview of Jitter Measurement Tools

This section provides a brief overview of the tools and methods for measuring jitter for HEL systems.

a. Cameras

Measuring jitter from a High Energy Laser at range is a difficult task. It is impractical to utilize the sensors used in labs to measure the beam profile and jitter due to their small size and limited incident power threshold. One method that has been used for many years is to indirectly image the beam as it is reflected off a diffuse surface. On land this can be achieved fairly easily, but for a surface or air target there are a number of challenges. There is not much real estate on airborne targets to place a camera and a scatter plate. A surface craft on the other hand should have no issue facilitating this setup. For simplicity, the land scenario will be described here.

This method allows for some of the energy to be dissipated upon reflection and the remaining energy to be attenuated enough to gather valuable beam characteristic data. The laser need to be incident on the scatterplate some angle off normal and the CCD sensor should face the plate at an equal angle opposite the laser path. The reflected energy could then be deposited onto a CCD sensor via a lens. There would have to be some correction for the angle of incidence in order to remove any distortion. There are some potential limitations for using this method for measuring jitter. One major limitation would have to be the frame rate and exposure time of the CCD sensor. If the sensor cannot capture frames at the rate the beam is jittering the calculation could have some error. Depending on the exposure time, smearing could occur from rapidly changing beam locations. Measuring total jitter at range is a challenging issue that is continuously being researched.

b. Shack-Hartmann Sensor

A Shack-Hartmann sensor is a type of wavefront measuring device, which functions by measuring distortions in the wavefront of incident light. Similar to a Differential Image Motion Monitor (DIMM), the Shack-Hartmann observes and analyzes light to measure some of its properties. This sensor could be employed on the test bed to validate the performance of imagers and atmospheric characterization instruments. When a beacon is placed on an airborne target, like the atmospheric characterization scenario described in in Chapter II, a Shack-Hartmann sensor can also be placed alongside a DIMM sensor to test and validate the system. The Shack-Hartmann sensor can measure the optical turbulence that is influencing the light originating from the beacon and provide information on the wavefront characteristics that the DIMM would not provide.

The Shack-Hartmann sensor consists of an array of lenslets that divide the beam up across the imaging sensor and a Complementary Metal Oxide Semiconductor (CMOS) or CCD sensor. Each lenslet focuses a small portion of the beam onto the imager. Through software analysis, the sectioned sensor can process any movement that differs from a uniform wavefront.

The distorted wavefront in Figure 72 causes the focused spots to be displaced across the sensor indicating that the incident wavefront have been distorted. This sensor can provide useful information related to intensity profile and wavefront characteristics.

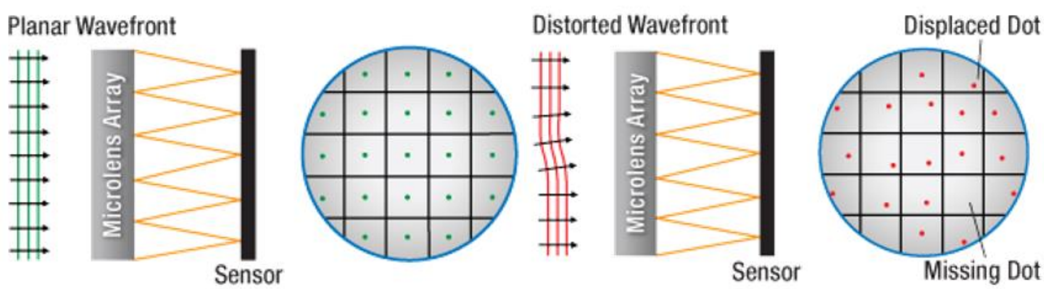


Figure 72. Shack-Hartmann Wavefront Sensor (from Thorlabs 2015)

F. SPATIAL PROFILE

The spatial profile of a beam is a key characteristic in determining the performance of a laser system at the target. This section describes the effects of a distorted spatial profile and provides methods for its measurement.

1. Overview of Spatial Profile

The spatial profile of a beam is defined by the variation of energy intensity perpendicular to the direction of propagation with respect to the distance from the center of the beam, as described in the class lab manual titled “Spatial Profile of a Laser Beam” from York University in the 2011 academic school year. Laser beam profiles may vary depending on the type of laser and the intended application; however, per the Spot Size discussion (Chapter IV, Section D), many of the laser beams utilized by HEL weapon systems are meant to emulate a Gaussian beam profile. In an ideal Gaussian beam, the location of the peak power can be assumed to be at the beam centroid and the relative beam power at any distance from the center of the beam is a known percentage of the peak power. However, the actual beam may exhibit a less than ideal spatial profile due to the presence of multiple modes besides the fundamental mode, TEM00. The particular spatial modes that constitute a laser beam can be dependent on the amplification generated by the laser cavity.

The spatial profile of the beam is typically illustrated by a 2 or 3 dimensional image that represents the distribution of energy across the face of a beam, as shown in Figure 73. The image on the left represents an ideal Gaussian beam with the associated energy intensity distribution, while the second image exhibits a distorted beam profile. Note the Gaussian-profile along the X- and Y-axes indicating the smooth transition through the center of the spot. In the distorted image at right, the intensity no longer follows the Gaussian profile. It should be noted that if merely spot size measurements were taken, the measurements would indicate a distorted beam profile based on a true spot size that is larger than calculated for an ideal beam; however, the beam's specific deviation from the ideal Gaussian profile would not be known.

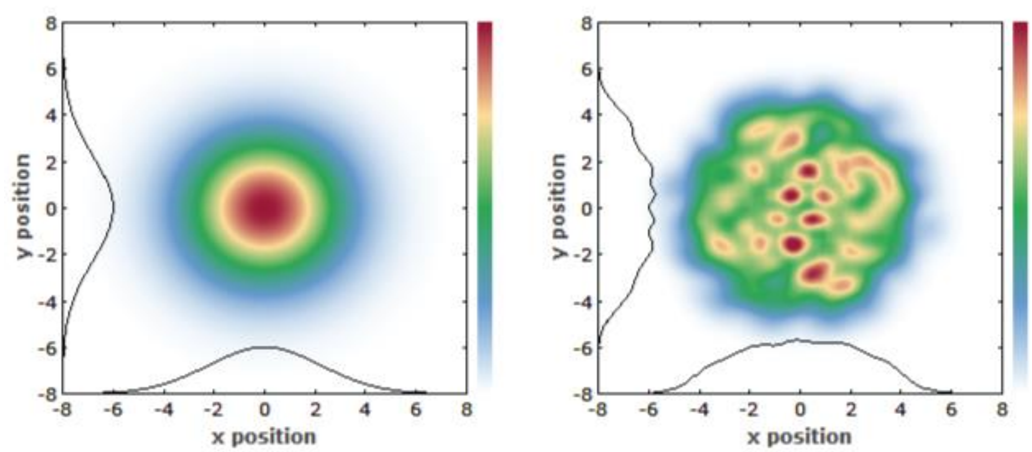


Figure 73. 2D Beam Profile: Ideal Gaussian beam (left) and Distorted Beam (right) (from Paschotta 2008c)

Mapping the beam spatial profile provides insight into several key characteristics related to the beam quality. A simple 2 dimensional image of the beam profile, as seen in Figure 73, can be used to determine the beam width. Beam width and its impact on laser performance is covered in greater detail in the discussion of Spot Size (Chapter IV, Section D). Viewing the entire 2D profile, rather than taking a diameter measurement from a single location, can provide an indication of any irregularities in the beam shape. Similarly, the 2D profile assists in the straightforward calculation of the beam ellipticity based on the comparison of the major and minor axis, which can be used for beam alignment (Roundy 2000, 33).

Other characteristics provided by the spatial profile involve the overall distribution of the beam energy. A 2D or 3D profile will quickly provide the location of the beam centroid, which should contain the peak power, assuming the system is producing a good quality beam. From the spatial profile, the relative beam power with respect to the distance from the beam axis can be calculated and compared to an ideal Gaussian beam profile. The Gaussian fit can be used to calculate the deviation between the actual and ideal beam profiles; however, some complex multimode beams can appear to be Gaussian and have minimal deviation from an ideal beam profile (Roundy, 2000: 35). Instead the calculation of the laser mode beam quality factor (M^2) has become more significant for judging beam mode and quality, although obtaining accurate measurements to calculate M^2 presents multiple difficulties, as outlined in Chapter IV, Section D. M^2 represents the difference between the TEM00 mode beam width and the actual measured beam width. An ideal beam profile will have a value of M equal to 1, whereas a beam comprised of multiple modes will have an M value greater than 1. The relationship between M2 and beam width is shown Equation 4.9 and Equation 4.10:

$$d_{TEM\,00} = \frac{4\lambda f}{\pi D_{in}} \tag{4.9}$$

$$d_{Actual} = M^2 d_{TEM\,00} \tag{4.10}$$

2. Applicability of Spatial Profile to HEL Testing

The spatial profile of a beam is a key factor in determining the performance of a system at the target. A beam with an optimal spatial profile will operate more reliably since the peak power will be contained at the beam centroid, provided the system is operating in near constant environmental factors. Knowledge of the beam centroid can be used to improve the effectiveness of targeting by allowing peak power to be more precisely applied to a desired target, assuming an accurate targeting system.

Operating with a distorted beam profile can cause an inconsistent distribution of the beam intensity and diminish the HEL weapon systems potential peak power. An estimation of the peak power degradation due to a significantly distorted beam profile was done by Ophir Photonics Group:

> In scientific applications nonlinear processes are typically proportional to the irradiance squared or cubed. Thus, a non-Gaussian profile may have peak energy as low as 50% of what a Gaussian beam would have under the same conditions of total power or energy. Therefore, the nonlinear process may deteriorate to 25% or 12% of what is expected. (Roundy 2000, 3)

The difference between an ideal Gaussian beam profile and a distorted beam profile is illustrated in the 3D Figure 74.

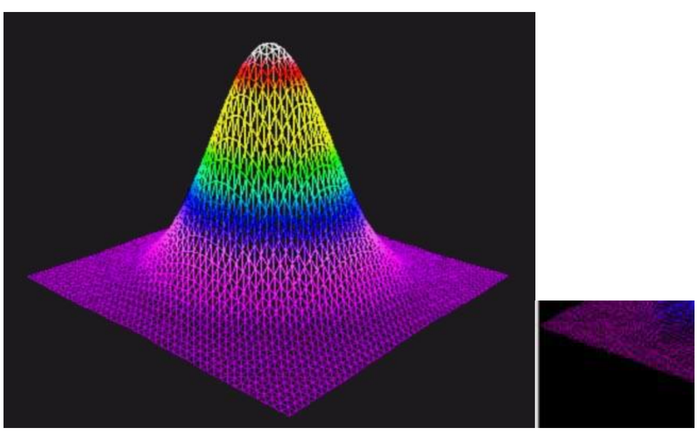


Figure 74. Ideal Gaussian Beam (left) and a Highly Structured Beam (right) (from Roundy, Carlos B. 2014)

3. Overview of Spatial Profile Measurement Tools

There are various methods available for mapping the beam spatial profile, differing primarily on their level on intrusion, hardware complexity, and measurement frequency. The two measurement systems predominantly used are a scanning aperture or a camera system. An overview of both these methods is provided below; however, they are described in further detail in (Chapter IV, Section D). A scanning aperture is a mechanical approach allowing samples of the beam energy to be taken by inserting a partially reflective surface into the beam path. This technique involves moving parts whose precise location must be taken into account when plotting the beam intensity data. Also, since the mechanical system collects intensity measurements for a single point at a time, the update speed for the displayed beam profile is limited to the speed of the moving assembly.

Similarly for the use of a camera system, some method must be employed in order to present a representative sample of the beam energy to the camera while preventing the oversaturation of the camera sensors. Insertion of either a partially reflective surface or a diffraction grating are options for reducing the beam intensity at the camera sensor. Unlike the scanning aperture, once calibrated for the particular beam intensity the camera system is capable of simultaneously mapping the entire beam profile based on pixel location. The ability to simultaneously view the entire beam profile allows for more accurate calculation of beam ellipticity and relative beam power distribution, since fluctuations in the beam profile would be quickly realized. With this method, the intensity measurements can be updated frequently, to provide a real-time visualization of the beam profile. Overall, the camera system would provide greater capability and simpler implementation.

G. MODEL AND SIMULATION

Modeling and simulation plays a major role in the design and development of a laser weapon system. This section describes how modeling and simulation aids in the testing and evaluation of systems under test.

1. Overview of Modeling and Simulation

There are countless benefits to utilizing Modeling and Simulation, from design of experiments, to performance prediction, to developmental and operational testing. Employing M&S can reduce costs, increase fidelity, predict future challenges, and potentially avoid unforeseen issues down the road. Furthermore, The Department of Defense strongly encourages the usage of Modeling and Simulation whenever applicable. It is defined as DOD policy in the DOD Instruction 5000.59 that:

> M&S is a key enabler of DOD activities… [The] tools, data, and services shall be visible and accessible within and across the DOD Components. M&S management shall develop plans, programs, procedures, issuances, and pursue common and cross-cutting M&S tools, data, and services to achieve DOD's goals by: promoting visibility and accessibility of models and simulations; leading, guiding, and shepherding investments in M&S; assisting collaborative research, development, acquisition, and operation of models and simulations; maximizing commonality, reuse, interoperability, efficiencies and effectiveness of M&S, and supporting DOD Communities that are enabled by M&S.

Since there is such a strong focus on Modeling and Simulation, it should come as no surprise that there are a myriad of M&S tools developed to support HEL testing. Subsequent sections within this chapter will discuss high-level aspects of several various Modeling and Simulation resources useful to directed energy testing.

2. Applicability of Modeling and Simulation to HEL Testing

Modeling and Simulation can help to show test planners what to expect during testing. This can help to identify "known unknowns" as well as "unknown unknowns," by iterating through numerous test scenarios prior to fielding a physical test.

M&S is a huge factor in the Validation and Verification of the results gained from testing. Of course, the models, simulation tools, and associated data must themselves undergo Verification, Validation, & Accreditation (VV&A). In fact, DOD instruction 5000.61 from the Under Secretary of Defense for Acquisition, Technology and Logistics (USD AT&L) mandates VV&A for all models and simulations. However, the models themselves can lend credence to the physical tests themselves.

Modeling and simulation tools aid in the evaluation, validation, verification, and accreditation of test results by comparing expected results to collected data. In the absence of computer modeling, it can be difficult to gauge 'ground truth' by which to compare the data yielded by test events. A question often arises during testing of how good is good enough, and how does one know that the numbers are "right?" Modeling and simulation can help to answer these questions.

Additionally, there is a feedback loop which connects the real-word test results back to the predicted results from the Modeling and Simulation efforts. Since no model can ever include the infinite permutations present in real-world scenarios, and no simulation can ever exactly embody perfect fidelity between the theoretical and practical, there is always room for improvement.

Many of the models useful to Directed Energy testing were developed in full or in part by the Department of Defense or other affiliated government entities. As such, the data collected from test events described in this testing architecture can be used to further reinforce these Modeling and Simulation tools. Often times, empirical data is used heavily in the creation of software models, and this is especially true when stochasticity plays a pivotal factor in the physical phenomenon in question. As such, additional data can be amazingly useful. As more and more tests are conducted, the lessons learned further increase the fidelity of computational models, compounding and multiplying the effectiveness of the test events.

3. Types of Modeling and Simulation Packages

There are of course, many different types of models, simulations, and analysis packages which can be useful to the High Energy Laser test bed. Many models and tools begin at the theoretical level, grounded in the fundamental physical laws which govern lasers, optics, propagation, and the propagation media (such as the atmosphere, which can be quite unpredictable). Due to the complexity of the phenomena involved modeling laser interactions, many of these software suites are broken down to look at specific aspects of laser systems. For the most part, these breakdowns can be grouped into two major categories.

One category pertains to modeling the action taking place within a laser itself. These models explore the internals of the laser system, including the power levels, wavelength, efficiency, and beam quality. The basis for these models is rooted in the fundamentals of how lasers work—such as the baseline optics and quantum laws, fundamental laws of refraction and wave propagation, and what input parameters drive those variables, such as input power, temperature, vibration, and signal noise.

A second category looks at the effects of the world around a laser system, and how that laser's performance is impacted by its environment. While other models look at a laser and its associated equipment such as pointing and tracking devices, beam controllers, and supporting systems, environmental models look at the factors which influence the system. That is, the models are bounded by the fact that some contributing factors to the laser's performance are not part of the system itself. These types of models tend to be more diverse, in that the operating environment of one laser system could be vastly different from another, and the implications of those differences could lead to drastically different ramifications. For instance, lasers propagating through the atmosphere can be wildly different from those propagating inside a lab environment, and the variables involved in atmospheric propagation can be literally as unpredictable as the weather. Similarly, propagation in maritime atmosphere can be vastly different from the atmosphere in a desert, or even from the littoral or coastal environment.

In the end, modeling and simulation tools are critical in the planning, conducting, assessing, and validating of test operations. This section will now elucidate the differences between major categories of modeling and simulation tools useful to the test bed, as well as a short description of a sample product used to perform that function.

a. Modeling of Laser Parameters

As mentioned above, one class of HEL modeling and simulation tools is designed to look at the parameters of a laser itself. WaveTrain is one such software that is commonly used for modeling laser systems. It is designed in an object-oriented system block diagram style, and is capable of simulating how a laser performs independent of its operating environment. Developed by MZA Associates Corporation for the U.S. Government and its contractors, WaveTrain is capable of simulating wave optics, modeling optical effects, modeling beam control system components, and simulating systems of beam control.

WaveTrain (Figure 75) accepts a number of inputs as factors considered by the model. These inputs vary from laser parameters, such as the HEL, steerable mirrors, optics, and beam directors, as well as taking certain external factors as an input as well, such as atmospheric parameters and engagement geometry.

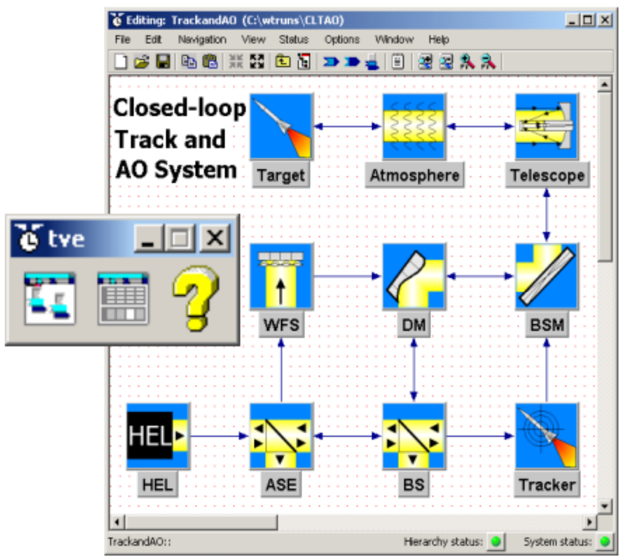


Figure 75. Visual Programming Environment for WaveTrain Setup (from Walker, Ben 2013)

Software packages such as this are particularly useful for understanding the impact of individual pieces of the laser weapon system being tested. Models can be run to simulate the role of wavefront sensors like a Shack-Hartmann array or to understand the performance of a deformable mirror assembly. By using the Zernike Polynomials, this kind of software is able to model optic parameters such as focus, astigmatism, and coma.

b. Modeling of External Factors

For modeling external factors to a laser system, such as atmospheric impacts and environmental interactions, the Laser Environmental Effects Definition and Reference (LEEDR) software suite is used extensively.

Developed by the Air Force Institute of Technology (AFIT) Center for Directed Energy (CDE), LEEDR takes into consideration a number of external factors and climatological data, such as season, time of day, and relative humidity. Furthermore, it relies upon a wealth of empirical data collected across the globe and up to 100km of altitude encompassing profiles of temperature, pressure, water content, optical turbulence, and particulate distribution. This wealth of information allows for laser scenario modeling at any number of engagement permutations, including air-to-surface, air-to-air, surface-to-air, and surface-to-surface at myriad frequencies.

Additionally, this model even goes beyond a simple table of location data to encompass almanac data as well. LEEDR includes a probabilistic climate database based on time, date, and season then extrapolates atmospheric profiles based on the testing location and scenario. The model also accepts live data feeds, such as the National Oceanic and Atmospheric Administration (NOAA) Operational Model Archive Distribution System (NOMADS), in order to supply up-to-date predictions out to 180 hours of the planned test event.

c. Hybrid Modeling and Simulation Packages

One predominate modeling and simulation package for understanding laser effects and the environment it is operating in, is the High Energy Laser End-to-End Operational Simulation (HELEEOS) (Figure 76). Developed by the Air Force Institute of Technology's Center for Directed Energy (CDE), HELEEOS is a tool to provide a realistic estimate of Directed Energy system performance in the scenarios defined by the testing environment it is operating in.

The model draws upon external sources, such as industry-developed tools by MZA Associates and Nutronics, as well as resources developed by AFIT. HELEEOS effectively models laser engagements in a number of locations and geometries, taking inputs on turbulence, scattering and absorption, meteorological and environmental data, as well as simulations from other models like LEEDR. That data is then used to simulate DE propagation and understand their impact on system performance.

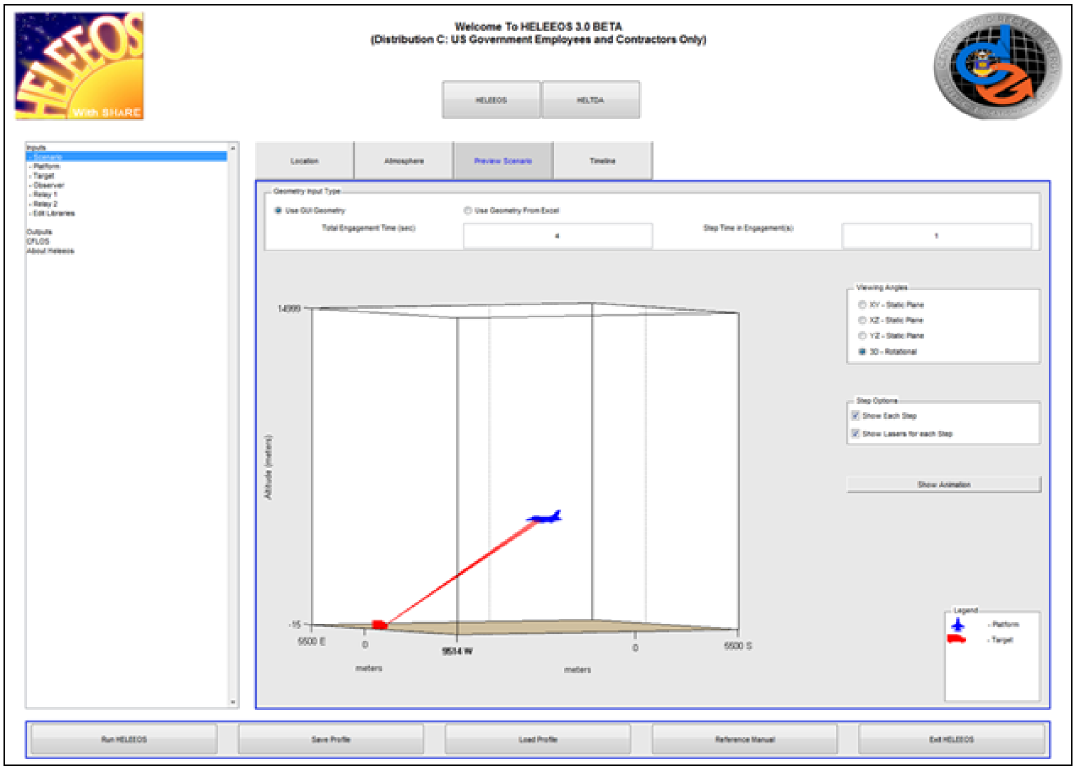


Figure 76. HELEEOS Simulation View (from Air Force Institute of Technology 2015)

Another commonly used modeling and simulation package is known as the High Energy Laser Consolidated Modeling Engagement Simulation, or HELCOMES. This tool was developed by the High Energy Laser Joint Technology Office (HEL JTO), as a way to include laser performance, atmospheric effects, and engagement simulations into one lightweight computer package written in the Java environment. HELCOMES is anchored in the wave optics software developed by MZA Associates, and integrates atmospheric impacts from a number of sources. This results in a comprehensive picture of laser performance and effectiveness in the applicable scenario being simulated using a light-weight, easy to use, and flexible architecture.

Two of the largest benefits of the HELCOMES software come from its extensibility and its flexibility. HELCOMES is able to freely accept a number of external simulations, parameters, and empirical data from a wide variety of other simulations and databases. This allows for a great deal of compatibility when planning tests in new environments where other tools might be unsuitable. The software is also extremely flexible and lightweight, owing to the fact that it is written in a straightforward Java language, it is able to be quickly run, modified, and optimized for rapid iterations in modeling and simulation for mission planning and analysis.

V. ANALYSIS OF ALTERNATIVES

Next in the Capstone's tailored SE staircase model was the analysis of alternatives (Figure 77) which included determining the most effective variant amongst alternatives and provided the opportunity to reflect on how well the underlying objective was accomplished.

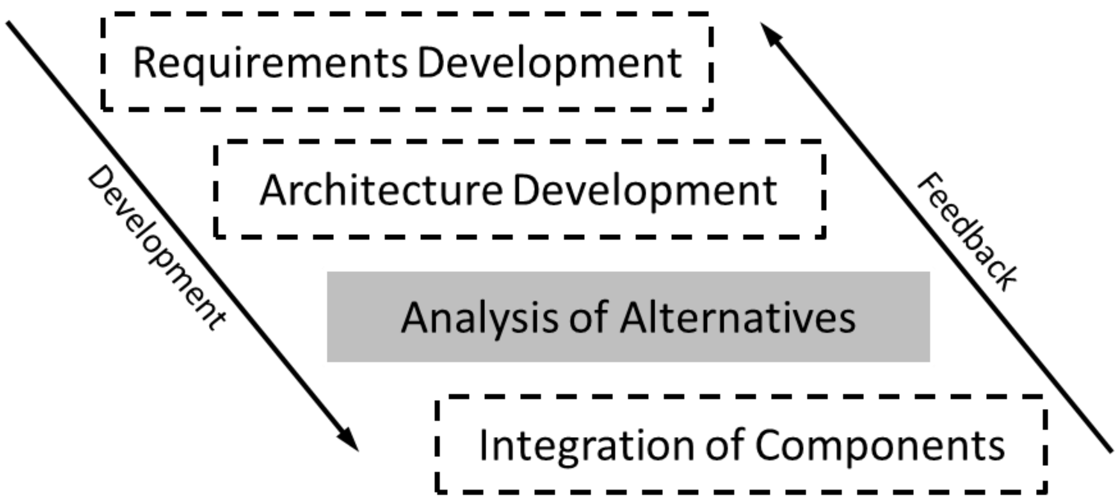


Figure 77. Tailored SE Process: Analysis of Alternatives Stage

The Analysis of Alternatives (AoA) was an essential and important element of the HEL test bed development and acquisition processes. The AoA used herein was not the traditional AoA as outlined in the Joint Capabilities Integration and Development System (JCIDS) process, rather a modified AoA used to identify the best alternative. A subjective risk matrix, decision matrix, and relative cost at equal effectiveness matrix were used to delve into the capability and mission worth of each alternative. The basis of this AoA was dependent on system requirements, relative cost, and risk as evaluation criteria to satisfy a capability need by the Navy to provide the most effective solution.

Three options were explored for this AoA: a centralized test bed, a decentralized test bed composed of multiple fully equipped ranges, and a fully equipped fly-away team composed of a single team equipped with all necessary instrumentation capable of deploying to any test range. Each of the implementations had pros and cons which required analysis of factors that would affect performance, cost, and schedule in support of Navy HEL testing. The selection criteria were knowledge base, location and logistics.

Knowledge Base reflects a suitable knowledge and expertise base which is composed of numerous engineers, technicians, and logisticians with specialized skillsets. It also reflects low collaboration across multiple activities to resolve technical challenges.

Location involves variability of weather which can limit year-round testing at any given range. This variability might also serve as a benefit assuming diverse weather conditions are required for testing objectives. Location also reflects an increased coordination effort for schedule de-confliction when potentially testing multiple HEL or Non-HEL systems in similar time frames.

Logistics reflects the lead time for and the restricted availability of equipment, instrumentation, and personnel. The potential for logistical mishaps also increase with the need to move both materiel and personnel. For example, test articles such as test ships, UAVs, and shore platforms must also undergo availability and transport requirements, as needed.

Figure 78 is a depiction of all the Major Range & Test Facility Base locations for all services capable of supporting some or all HEL test bed requirements. Note NSWC Dahlgren is not a MRTFB asset.

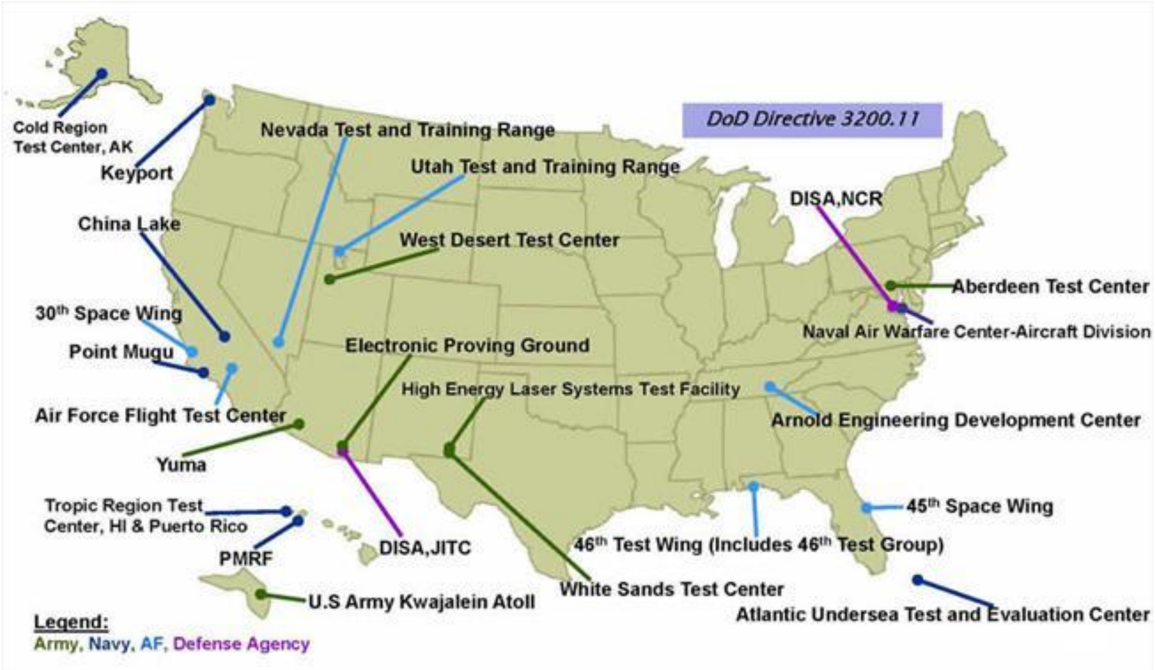


Figure 78. Major Range and Test Facility Base Locations (from Department of Defense [AT&L] 2007)

A. CENTRALIZED TEST BED

The theory behind a centralized test bed is that the core elements which comprise this test bed would reside in a central location, a Navy test range in this case. This implies that the primary location for the Navy to test laser weapon systems in a maritime environment would be at this central test range. This is not to suggest that factors not considered in this study would not drive a customer to test in a different location due to individual mission specific weather, geography, or humidity requirements for differing HEL systems. However, the majority of Navy testing, requiring the parameters outlined in this thesis, would happen in one location.

The investment in equipment to support high powered laser test and evaluation would, in theory, only be made once. This could potentially save the government money by reducing the logistics associated with managing multiple sets of equipment. Ideally, this location has access to a Navy test platform, as this would be required to test any weapon systems in a relevant maritime environment. In this construct, all personnel with the required subject matter expertise should be located at the single location so that minimal personnel are required to travel to the location to support the laser test bed. There would be considerable savings in training one set of engineers, technicians and support personnel vice multiple teams having to be trained in different locations. Over time the HEL test team would possess a knowledge base that better ensures tests are conducted effectively and efficiently, saving tax payer dollars.

1. Historic Example

An example of one of the few Navy test ranges that has been used in the past to support HEL testing is Naval Base Ventura County (NBVC). NBVC possesses most, if not all, of the capabilities described for a centralized test bed in this thesis.

NVBC served as the T&E Lead for the ONR MLD program and is the homeport for the ex-USS Paul F. Foster (DD-964), which is a dedicated Navy test platform, where the program integrated the ship's power, SPQ-9B queue, and NAVSSI to the laser system aboard the test ship. The program utilized San Nicholas Island as a sea-based platform as well as a backstop for multiple laser test events. This is a useful example of what could be a centralized test bed location, but considering there is not currently a central location, the execution of these tests are done in a very inefficient manner as described in the decentralized test bed historic example (Chapter V, Section B).

2. Test Methods

The centralized test bed should also possess the sensors, required instrumentation, and modeling and simulation support for test events. Ideally, all required testing should be able to be satisfactorily completed without having to reach out to external entities. All requirements and scenarios described (Chapter II, Section D) should be achievable at this single location.

B. DECENTRALIZED TEST BED

The idea of having multiple equipped ranges is essentially an extension of the fully centralized test range, in various locations. All locations will be able to fully support HEL testing that will satisfy test scenarios and requirements discussed in chapter II. As can be immediately seen, the cost for this alternative will be significantly higher because multiple sets of equipment would need to be acquired and multiple teams of engineers and technicians will need to be trained.

On the other hand, this will definitely alleviate any scheduling issues that may arise from having only one fully equipped test range available. With HEL weapons quickly on the rise, the amount of testing before weapons are fielded is expected to significantly increase. Having multiple equipped ranges may be a high cost option to begin with, but it has its benefits with regards to the availability of equipment and the amount of subject matter expertise that will be available after the initial startup costs.

1. Historic Example

MLD is an example of how multiple equipped ranges have been used for testing. MLD conducted tracking test events at NBVC 2010, a land demo at Dahlgren 2010, and an at sea demonstration back at NBVC 2012.

2. Test Methods

The test methods for multiple fully equipped ranges closely resemble that of a single fully equipped range. Each location should be able to fully and satisfactorily meet all requirements with minimal reach out to any external entities. An added benefit of having multiple equipped ranges is that equipment and expertise can be shared between sites, if the necessity to do so arises.

C. FULLY EQUIPPED FLY-AWAY TEAM

A fully equipped fly-away team would consist of subject matter experts (SMEs) throughout the country who come together for mission specific test events at any applicable test site. All the necessary equipment and sensors would be shipped to the designated test site for that specific test event. The event duration could range from a few days to a couple months. Currently, this is the approach that is used for conducting HEL testing. Several engineers and technicians (government and contractors) all converge at an existing range and conduct the testing.

1. Historic Example

An example of fly-away teams approach has been utilized in the past to test HELs. MLD completed a tracking demonstration at NBVC 2010, followed by a lethality demonstration at NSWC Dahlgren 2010. Open-ocean testing onboard test ship NBVC 2012.Each test event required specific test equipment, operators, engineers, and range capabilities to assess MLD. SMEs and instrumentation were transported to each site to conduct testing.

2. Test Methods

Having a fully equipped flyaway team will consist of a large number of personnel traveling to a single location each time HEL testing is to take place. The ranges will already exist, but they will be supplemented with equipment that is shipped to the site in order to accomplish successful HEL testing that will meet all test requirements and scenarios. The equipment being shipped will cause it to undergo more wear and tear due to simply being constantly shipped and handled from one location to the next.

D. RISK ANALYSIS

Alternatives for the HEL test bed were analyzed for risk in terms of performance, schedule, and relative cost drivers. High-level risks were identified and quantified in order to perform a trade-off analysis. Risk matrices were used to communicate the Likelihood (L) and Consequence (C) of identified risks and to categorize them in three levels: low (green), moderate (yellow), and red (high). Likelihood and consequence criteria are shown in the appendix. The three test bed alternatives were assessed on the following attributes: Knowledge Base (performance), Location (schedule), and Logistics (schedule).

1. Centralized Test Bed

Having a centralized test bed will reduce the Knowledge Base technical risk because all the required knowledge, equipment, and expertise will be in one central location. Collaboration is more readily available without the need to work across multiple activities that are potentially in different time zones.

A centralized test bed can increase the Locations schedule risk resulting from an increase in workload for a single location. Particularly, if several different programs are attempting to test their HEL weapon at the same time, schedule de-confliction will become a significant part of the Standard Operating Procedures (SOP) of the test bed. This includes range schedule de-confliction, as well as test article (surface, air, and shore) schedule de-confliction.

The Logistics scheduling risk is low due to minimal movement of personnel, equipment, and instrumentation. Test instrumentation transport would also be minimized given they are an asset and owned by the centralized location.

Performance and schedule risks identified for a centralized HEL test bed are shown in Figure 79.

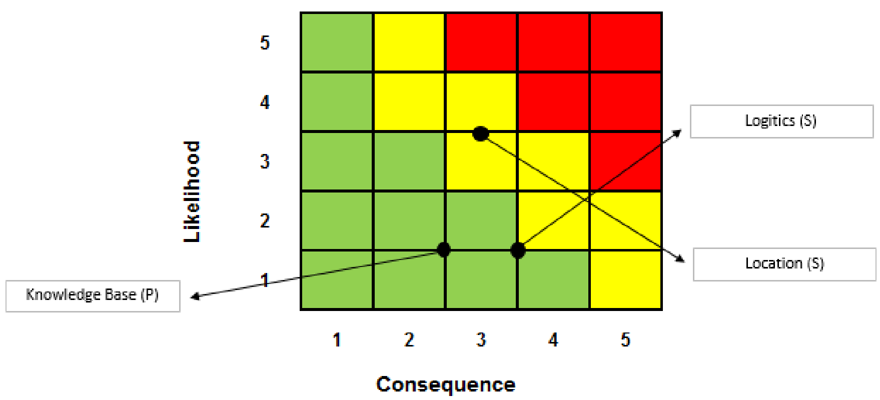


Figure 79. Risk Matrix for Centralized HEL Test Bed

Having a centralized test bed can increase maintenance costs due to costs related to operational sustainment and minimizing the Mean Time Between Failures (MTBFs). Since equipment will be used more often at a single location, the periodicity of corrective and preventive maintenance will increase. However, a centralized test bed will reduce costs in the long term as the demand for HEL testing increases. Major instrumentation, equipment, and personnel do not have to be transported from other activities to support tests because these assets already reside in one location. The cost drivers associated with the centralized test bed include equipment procurement, support personnel, facilities, and equipment maintenance.

2. Decentralized Test Bed

Having multiple equipped ranges will increase the Knowledge Base risk because all the required knowledge, equipment, and expertise are available in several different locations. This approach utilizes a collective knowledge and expertise base composed of numerous engineers, technicians, and logisticians with specialized skillsets across multiple locations. This poses potential collaborative challenges when working across multiple activities to resolve technical challenges and HEL assessments in a timely, consistent, and standardized manner.

Having multiple equipped ranges can reduce the Location schedule risk. This will prevent test event pile up at a single location and allow for more test events to take place concurrently as HEL testing demands increase. HEL systems can choose from multiple test bed locations. Variability in weather would have a lesser impact because HEL systems under test can plan for a location where the weather is more favorable.

Performance and schedule risks for a decentralized HEL test bed consisting of multiple locations are shown in Figure 80.

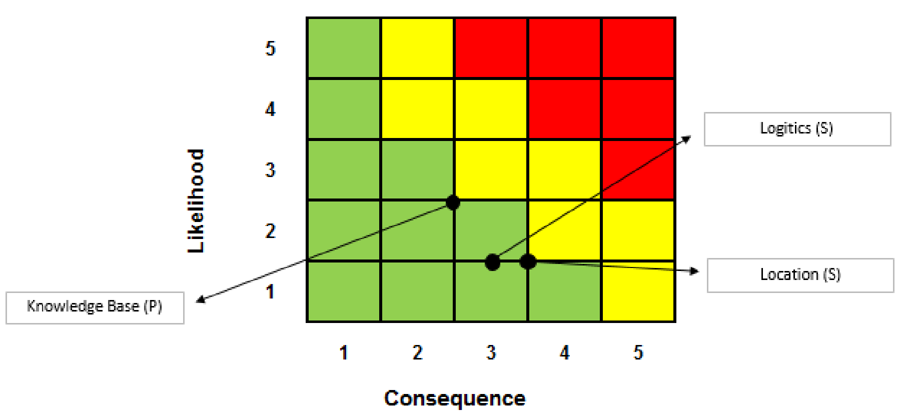


Figure 80. Risk Matrix for Decentralized HEL Test Bed

The cost to equip and maintain multiple fully equipped ranges will be high due to the cost of having one fully equipped range, multiple times over. However, with the demand for fielding DE weapons increasing, this may be the best option. Filling the initial expertise demand for the selected test beds will increase the knowledge base risk but will ultimately decrease in risk. Also, since multiple sets of equipment will be employed, the MTBF of any one piece of equipment will increase and the amount of corrective and preventive maintenance will occur less frequently. The cost drivers associated with the multiple equipped ranges approach include equipment procurement, support personnel, and facilities. Since there will be several fully equipped test ranges (three assumed for this AoA), test equipment will not be used as frequently. Consequently, equipment maintenance is not a significant cost driver.

3. Fully Equipped Fly-Away Team

Having a fly-away team will cause personnel to be dispersed all throughout the country, which will reduce regular face-to-face technical communication. This will increase the Knowledge Base risk by decreasing the rate at which knowledge is exchanged, and in turn delay tasks such as completing test plans or test manuals in a timely manner. The Location schedule risk for a fly-away team is moderate to high because of the extended amount of time required to get all parties involved to travel to the same location and the added amount of time it will take to coordinate and ship materiel.

Performance and schedule risks for a HEL test bed consisting of a fly-away team are shown in Figure 81.

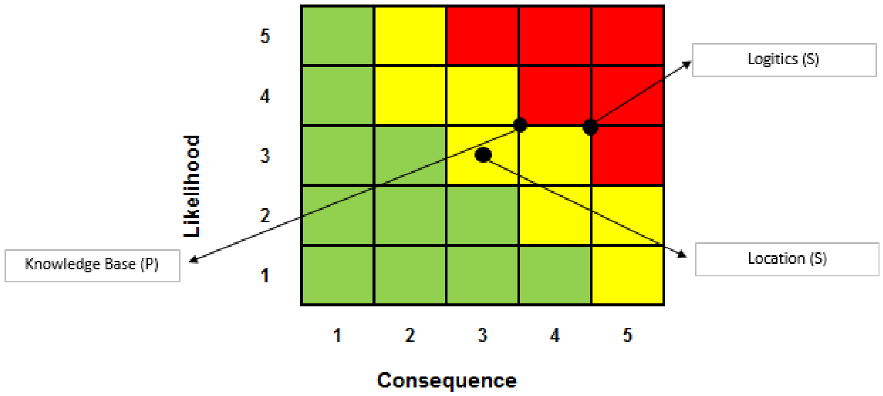


Figure 81. Risk Matrix for Fly-Away Team

Having a fly-away team will increase costs due to constant transportation of personnel and materiel. Also, equipment will need to be maintained at more frequent intervals due to constant shipping and handling. More sets of equipment will have to be purchased to ensure equipment is available when testing is scheduled, and not for example, in transit to/from a different site.

The cost drivers associated with employing a fully equipped fly away team include equipment procurement, support personnel, equipment maintenance, and transportation of personnel and materiel.

4. Trade-off Analysis

The three HEL test bed alternatives were assessed for architecture, resource readiness, and relative cost drivers at equal efficiency. Each HEL test bed variant was evaluated on the following subjective attributes: Knowledge Base, Logistics, and Location. All three alternative options were subjected to a risk analysis and decision matrix.

Risk analysis was presented using risk matrix models shown in the previous sections which consisted of two dimensions: the likelihood (L) of failing to achieve a particular outcome, and the Consequence (C) of failing to achieve that outcome. Subjective data to produce the matrices are shown in Table 9.

Table 9. Risk Levels for Identified Attributes

Risk Levels for Identified Attributes									
Alternative	Knowledge Base (P)			Location (S)			Logistics (S)		
	C	L	C * L	C	L	C * L	C	L	C * L
Centralized	2	1	2	2.5	3	7.5	3	1	3
Multiple Equipped	2	2	4	2.5	1	2.5	3	1	3
Fly-Away Team	3	3	9	2.5	2.5	6.25	4	3	12

The risk analysis revealed some very valuable and tangible information which was then used to determine which approach has the lowest risk across all selected attributes. As in Table 9, the alternative with the lowest Knowledge Base risk traced to the centralized approach. Having multiple fully equipped ranges yields the lowest location risk. Both the centralized approach and multiple equipped ranges had the lowest Logistics risk. Two out of three of the highest risk values were identified from the fly-away team. Based on the risk level matrix, and decision matrix, it appears that the centralized location is the best option. A decision matrix was generated using subjective comparisons within alternatives to assign attribute scores for each alternative ranging from 1 (worst), 3 (below average), 6 (above average) and 9 (best). After reviewing the decision matrix raw scores in Table 10, and a graphical representation in Figure 82, a centralized test bed results as the best alternative when using a decision matrix

Table 10. Decision Matrix

Decision Matrix					
	Criteria			Results	
Systems	Logistics	Knowledge base	Location	Raw Score	Rank
Centralized Test Bed	9	9	6	24	1
Fly-Away Test Team	1	6	6	13	2
Decentralized Test Bed	3	1	1	5	3

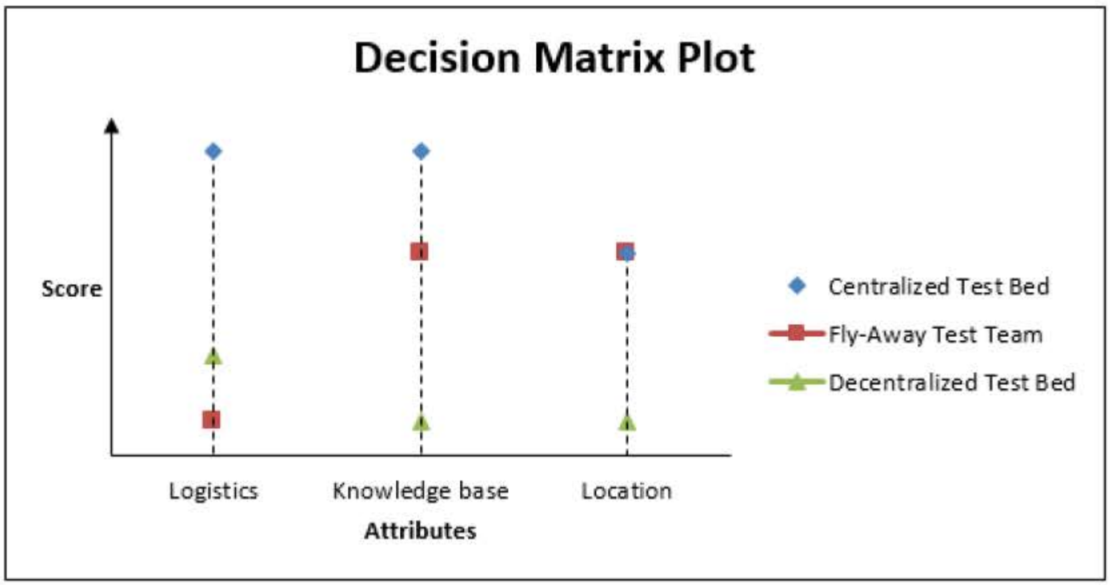


Figure 82. Decision Matrix Plot

The preceding considered the technical and schedule aspects. The following will demonstrate the subjective cost drivers associated with each alternatives shown in Table 11. In this instance relative cost scores ranged from 1 (Best), 3 (Medium) and 9 (worst). The cost drivers under test are shown in Table 11 with their assigned scores.

Table 11. Relative Cost at Equal Effectiveness

Relative Cost at Equal Effectiveness							
Systems	Cost Drivers						Raw Score
	Equipment	Support Personnel	Facilities	Equipment Maintenance	Travel	Shipping	
Centralized Test Bed	3	3	3	1	1	1	**12**
Fly-Away Test Team	3	3	3	1	9	9	**28**
Decentralized Test Bed	9	9	9	1	3	3	**34**

The relative cost associated with the centralized location is significantly less than the multiple equipped approaches. This combined with the lowest Knowledge Base technical risk and equally low Logistics schedule risk, makes the centralized location the best option to pursue.

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VI. INTEGRATION OF COMPONENTS

This section discusses the "integration of components" step in the Capstone's tailored SE staircase model (Figure 83). In this step the team performed component synthesis to meet stakeholder requirements and demonstrate component functionality.

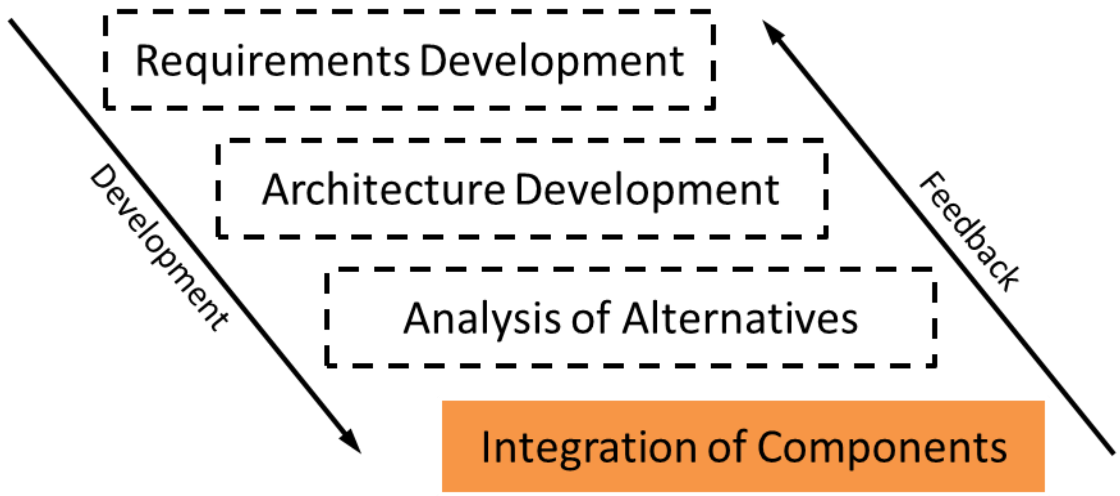

Figure 83. Tailored SE Process: Integration of Components Stage

The HEL test bed architecture has been depicted and many of its components have been defined. The challenge remained to integrate the components to synthesize them as a coherent system into their environment. The goals of modularity and scalability posed great challenges. System integration needed to take into account the various AoAs. Additionally, the test bed needed to be verified and validated by the stakeholders.

A. INTEGRATION

Integration concerns vary based upon the alternative selected. For example, the centralized test bed will not require the same size and mobility constraints that the fly-away team alternative will. The following integration issues were identified within each alternative's specific scope. Though largely similar, each test bed alternative offers its own unique integration concerns.

1. Centralized Test Bed

A single test location will allow for a high concentration of resources. There will be more availability of specialized personnel. Testing areas can be refined with specific infrastructure built rather than repurposed. Dedicated firing lanes can be cleared and remain clear. Investments can be made into stabilized mounts with known parameters, and fleets of mobile, realistic targets. Controls, safety, power, and operating systems can all be developed for the purpose of testing and made permanent. The permanence of the facilities would require its own full time maintenance and support. Environmental and atmospheric data can be continuously gathered facilitating high fidelity modeling and simulation. Scheduling will be a limitation and will likely require a dedicated planning entity.

2. Decentralized Test Bed

Multiple test locations will have similar integration concerns to the centralized approach, but will require more personnel and funding to staff and support. This may allow each location to focus on a specific type or mode of testing rather than dispersing funds into all types of tests. One location might focus on overwater aerial engagements, for example. The total funding budget would be split amongst the multiple locations, limiting the ability to build new infrastructure. Thus, there will be more reliance on pre-existing infrastructure. Scheduling concerns would be alleviated do the presence of multiple ranges.

3. Fully Equipped Fly-Away Team

Mobility of components is of great concern. They need to be broken into pieces that are no more than 50 pounds to facilitate transport via air and hand-carry by personnel. Interconnectivity to different operating systems and power supplies will also be of great concern. A mobile team will have to establish a base of some location, requiring a large storage facility to keep equipment not required for a specific test. A support facility would also be required to maintain equipment between uses. There will be a high reliance on pre-existing infrastructure at each location. There will be existing buildings, roads, and utilities that will need to cater to the implementation of test bed components. Similarly there will be pre-existing building (residential communities for example) that may preclude the usage of an otherwise ideal location.

B. INTERFACES

This section will discuss the interfaces between components when the test range and a laser weapon system are included. These two components are not part of the architecture but nevertheless will be involved in the implementation of the HEL test bed. Figure 84 shows the interfaces. There are two primary interfaces connecting the HEL test bed: an interface to a power source and an interface to a control system used for controlling the numerous components of the test bed. These two main interfaces will now be discussed further.

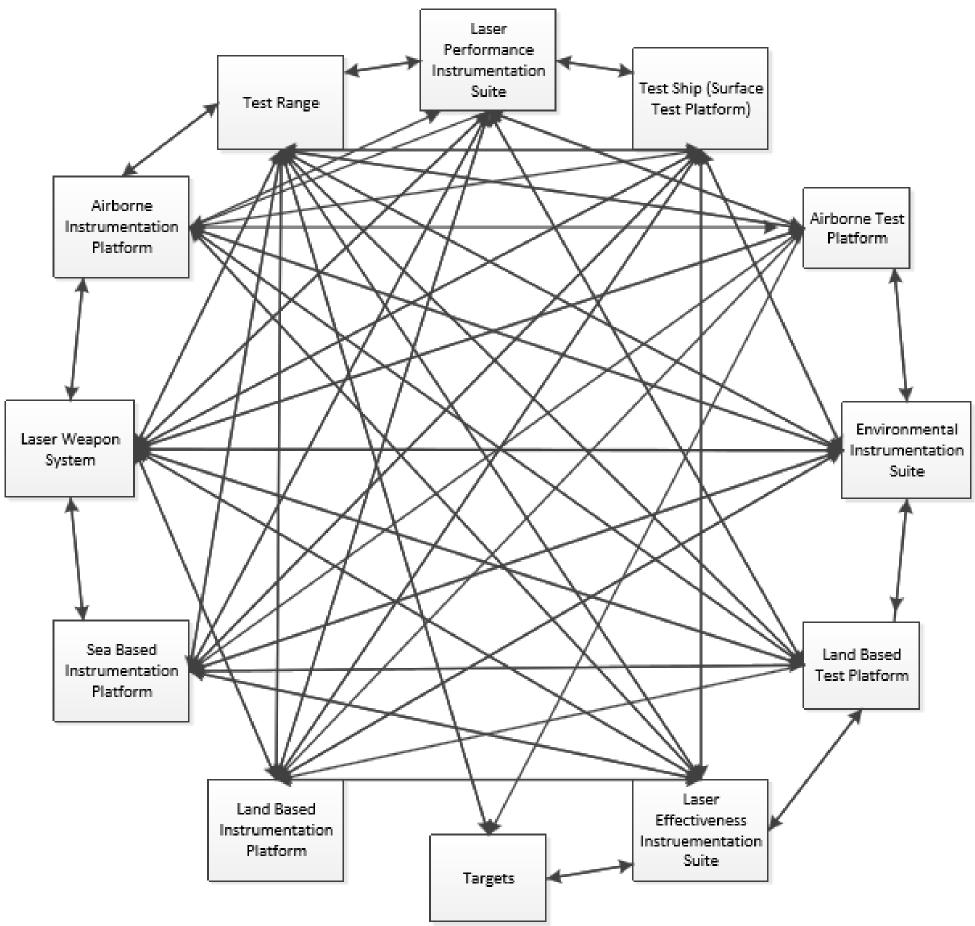

Figure 84. Interfaces

In all stages of testing the HEL test bed, components and laser systems will require power. In the early stages of testing conducted on land, a power source can be brought in for all equipment. However, in later stages, the testing of a laser's power requirements, as well as some of the laser instrumentation, will have to be supplied by an operational test platform such as a test ship of test aircraft. A standard interface to this power is needed to ensure compatibility with all systems conducting testing on the range. Other instrumentation not onboard the test platform will also require a standardized and stable power supply. Specific power requirements will vary from test to test based upon scale, duration, amount, and type of instrumentation required. A thorough analysis of these requirements should be completed in the planning stages of any test to ensure an adequate supply, with the right parameters, exists during testing.

The second interface, an interface to a control system, is required for the various instrumentation and laser systems for HEL testing. This interface will require numerous controls compatible with a wide range of instrumentation which will be gathering data during test events. A control system is required to control and link the components together. Instrumentation, sensors, targets, and the laser itself will need to be controlled simultaneously for a successful test. Data gathered needs to be saved, easily transmitted, and in a format readily usable by current and future modeling and simulation software. Consideration should be given to modularity and mobility to facilitate varied tests. Since HEL systems often spend many years in development, upgradability is crucial. Current DOD usage of Microsoft systems should be taken into account, but not necessarily defaulted to.

The other interfaces vary from a simple coaxial cable or mounting bracket, to a complex maintenance and support system. The range will contain the test bed. It will provide power and infrastructure for the various instrumentation suites. The environmental suites would likely operate on a more regular basis, including when a laser is not being tested, to facilitate data collection for range weather modelling. The range would house the majority of the mobile targets for the duration of their use. Even targets not inherent to the range (they are brought by the fly-away team for example) will still reside on the range during the tests. Fueling, maintenance, and other support will be required such as docking facilities for maritime targets and launching/runway facilities for the aerial targets. It would supply mounts or mounting locations for stationary targets and the various instrumentation suites.

The range will contain the laser weapons system. For safety, it should contain any and all output from the laser. In some cases, it must provide the power for the laser. The test platform would also reside on the range. The platform itself needs to be maintained, supplied, and crewed. The platform, such as a test ship, represents a sizeable investment by that range for maritime testing.

As mentioned, the targets will require interfaces with the range. Stationary targets will require stabilized mounts and mobile targets would require individual maintenance support. Certain targets will carry instrumentation requiring bracket mounting. All test platforms, will interface with the targets in several ways. First, they would engage targets. Second, they will likely exercise a degree of control over the targets for safety and efficient testing. The target must be within range for a test shot, but not heading toward the ship like a guided missile.

The laser weapons system's interfaces would vary based on the type employed. All would reside on the range and be employed on one of the test platforms. Each platform would require the ability to mount, aim, power, and control the laser. The various instrumentation suites would need to be closely arranged such that laser data is gathered at the firing point, mid-beam, and at the target.

As mentioned, each test platform would reside on the range and would require support. Airborne- and land-based tests would require a hangar or storage facility to protect materiel from the elements between tests. Many previously mentioned test ranges have land-based platforms. They can be leveraged to produce an exhaustive list of required interfaces and serve as an example.

Because of its smaller scale (e.g., UAVs), the airborne platform would likely carry only the laser weapon system and some instrumentation due to load limitations. Size and weight would be prime factors here, as fuel and aerodynamics cannot be altered greatly to remain airworthy.

The test ship also has challenges. The ship needs to be of adequate size to carry the HEL and test team, and have adequate power available to support the HEL and its instrumentation. It would likely consist of power, support, and control for some portions of the instrumentation. There would also be an interface in which the test ship would gather data from instrumentation separate from itself. The test ship would require the following interfaces with the instrumentation and laser weapons systems: power, control, data transfer, and mounting. The instrumentation would need to be mounted on the ship, along the firing line, and at the target. Control and data links would be required to connect the ship with shore-based infrastructure on the range. Based out of NSWC Port Hueneme, the ex-USS Paul F. Foster can serve as an example for the requirements and interfaces needed by a test ship.

C. VERIFICATION AND VALIDATION

Dr. Gary Langford in *Engineering Systems Integration* defines verification and validation. Verification is the process of confirming the truth or accuracy by describing the characteristics of interactions, the enactments of mechanisms or procedures or the consequences of Energy, Material, Money, and Information (EMMI). Validation is "an assessment of the operational system that exposes and quantifies the systems' limitations" (Langford 2012, 373). Verification asks "Does the system work?" while validation asks "Is this the right system?" The intent of this process is to determine if the user's needs are satisfied for the different scenarios.

The system was verified or can be verified in two main ways. First, the model-based approach allowed us to view the main components and discern any missing functions or components. The system laid out in that format ensured the presence of all required components.

Second, the modularity and the ability to alter the scope of the test bed will allow users to verify their components before attempting to integrate them into the system. Components that fail to perform as required can be readily exchanged. There is also the capability to readily use experimental components (sensors, instrumentation, etc.).

The system was validated by the team re-examining the stakeholders' original requirements to ensure that their needs and wishes were fulfilled. This was done systematically by tracing the portion of the architecture that fulfilled each requirement in each of the multiple scenarios.

For future work, meetings are recommended with the major stakeholders to garner feedback on the report. The report began with the gathering of stakeholder requirements, and thus the stakeholders have the action to validate the report. The multiple components need to work in and of themselves; they also must work together as this meant to be an all-inclusive test bed. Revisions are recommended based on their input and results from their usage.

The DE community, particularly the activity based at NSWC Port Hueneme, is with a primary stakeholder. Their mission is the Research and Development of DE and HEL weapons and, their concurrence is imperative to ensure V&V of the test bed. The SPAWAR atmospherics branch should provide general feedback, specifically that regarding the environmental and atmospheric aspects of the architecture. Ultimate validation of the HEL Test Bed will be achieved when it is implemented on an active range.

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VII. SUMMARY

Since September 2014, the Navy's Laser Weapon System, LaWS has been operationally deployed aboard the USS PONCE. "We've tested it in the lab. We've tested it operationally at sea. Now, we are not testing it anymore. This is operational," said Rear Adm. Matthew L. Klunder, chief of naval research at the Office of Naval Research. "They are using it every day" (Osborn 2014a). The 30 kW laser has been used for targeting and training exercises against an array of targets of varying size and speed. It has been fully integrated into the ship's navigation systems radar and CIWS. LaWS has proved itself durable and functional in various weather conditions. Current calculations have its cost per shot at about 59-cents. The accomplishment of this deployment is paving the way for putting HELs on other ship platforms.

"The Navy currently has 62 ARLEIGH BURKE class destroyers (DDG 51s) currently in service and six Flight IIA-model destroyers under construction with plans to potentially build as many as 22 next-generation Flight III DDG 51s…Laser weapons and electromagnetic rail guns are among some of the upgrades being considered for the Navy's fleet of destroyers," said Capt. Mark Vandroff, DDG 51 program manager (Osborn 2014b).

The success of LaWS marks an important milestone in HEL development. Future research and development will continue increasing the power, reliability, and utility of the weapon. These weapons will be tested and fired to ensure their performance and effectiveness meets the stakeholders and ultimately the warfighter's requirements.

In Chapter II, the stakeholders' requirements were decomposed, developed into CONOPS, and defined with specific scenarios. Range capabilities were described that would enable these scenarios to take place. Three architectures are created. The physical architecture shows what components are required for the test bed. The functional architecture defines what must be done by the test bed. The allocated architecture assigns these functions to their corresponding components so that all the requirements are met. Following this architecture provides a baseline for the development and implementation of a test bed that fulfills the many maritime testing requirements.

Chapter III delved into the HEL test bed architecture, and provides an invaluable tool to facilitate their development. By utilizing a systems-based approach for the development of the Navy's HEL test bed, the system is viewed in its entirety: components, inputs, outputs, controls and constraints, and their interactions with each other and with external entities. This will allow for the most efficient usage of available Energy, Matter, Material wealth and Information (EMMI). Due to the modularity of the design, the test bed can be scaled to fit any location, and architecture will long out last the current test equipment.

Chapter IV offered an in-depth analysis of the myriad of sensors and instrumentation currently in use and the concept of operations for deploying this instrumentation on the test bed. Additionally, it defined precisely what these sensors measure in relation to the performance of a HEL. Though not exhaustive, it provided an excellent survey of what types components might be used in building the test bed while allowing for technological advances.

Chapter V provided a discussion and analysis of alternatives of several implementation methods for the test bed: Centralized, Multiple Ranges and a Fully Equipped Fly-Away Team. Risk analysis was performed to include a trade-off analysis for these options. The Centralized option was shown to be superior; however, this would be a deviation from the current way tests are performed (e.g., flying small testing groups to a variety of locations for the duration of the evolution). Consideration for sustaining a knowledge base across multiple ranges was one of the major factors in the risk analysis. There were some schedule concerns if a single range was selected to host all laser testing which is currently infrequent, but may soon be common. An extensive range evaluation should be conducted for further study.

Finally, Chapter VI touched on the system's synthesis into existing infrastructure, and described how its components will integrate and interface with each other and external entities. The interface between existing ranges and this new capability was also discussed. There are inherent capabilities on all MRTFB ranges that will aid in the successful execution of the HEL test bed.

Potential future research would include the aforementioned comprehensive range study to clearly identify the ranges capable of supporting this mission for the Navy. The essential elements have been described herein and few military ranges can fully satisfy these requirements. Also, due to time constraints and accessibility of information, future study might entail a more in depth cost analysis to provide additional resolution into the cost and comparison between alternatives. Nevertheless, through research and continuous interaction with the active stakeholders, all questions that were sought out to be answered have been fully addressed in this thesis.

No longer within the realm of science fiction, HEL and DE weapons are here and now, and operationally deployed on a U.S. Navy ship. "We've done analytical work and we know what ships we can put it on. Frankly there are a lot of them in the naval inventory. We're talking through which ones we might want to do in the future, specifically those more suited to the higher power 100 to 150 kilowatt laser," Rear Adm. Klunder said (Osborne 2014a). The HEL test bed will help to ensure their future success.

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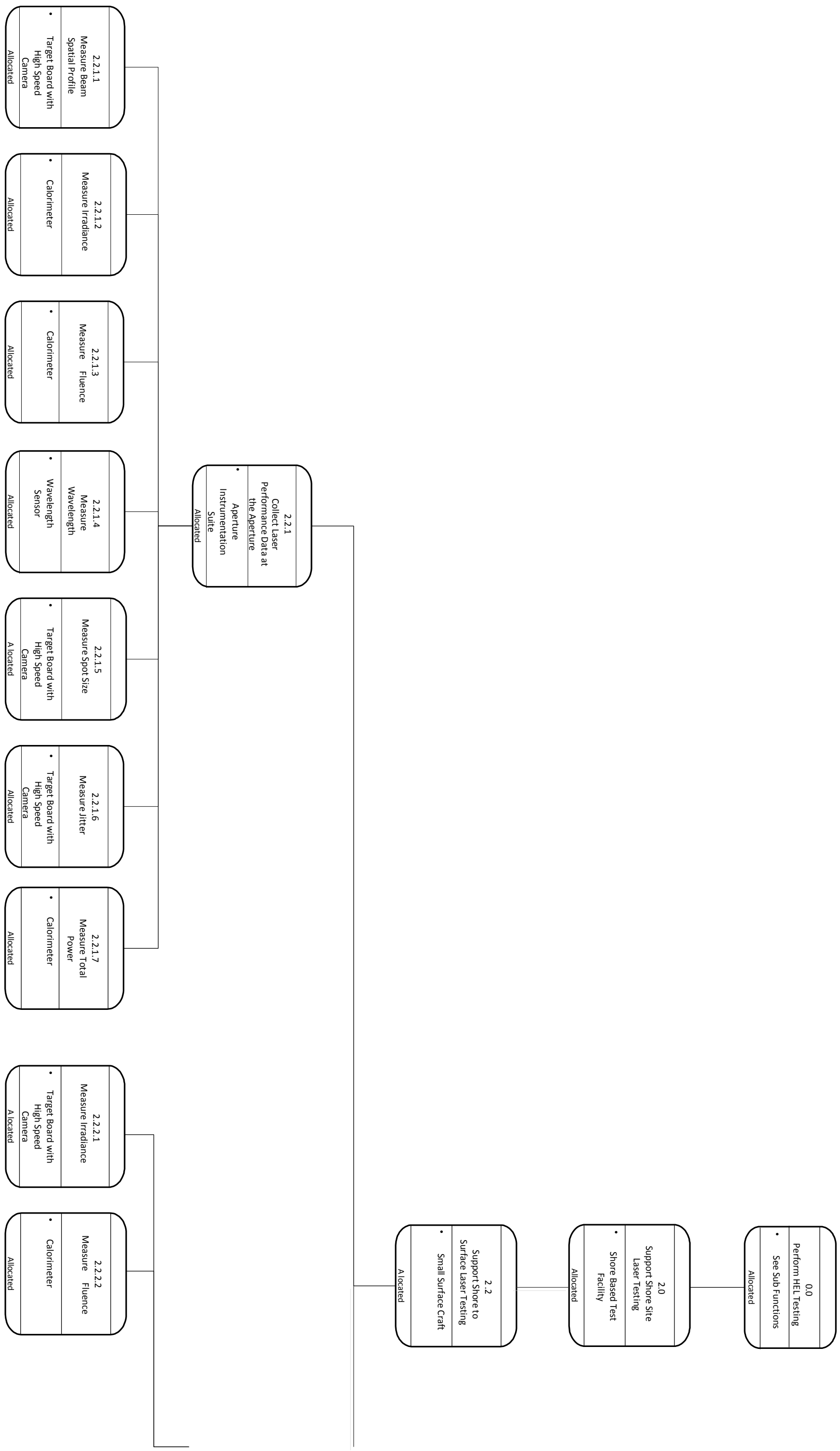
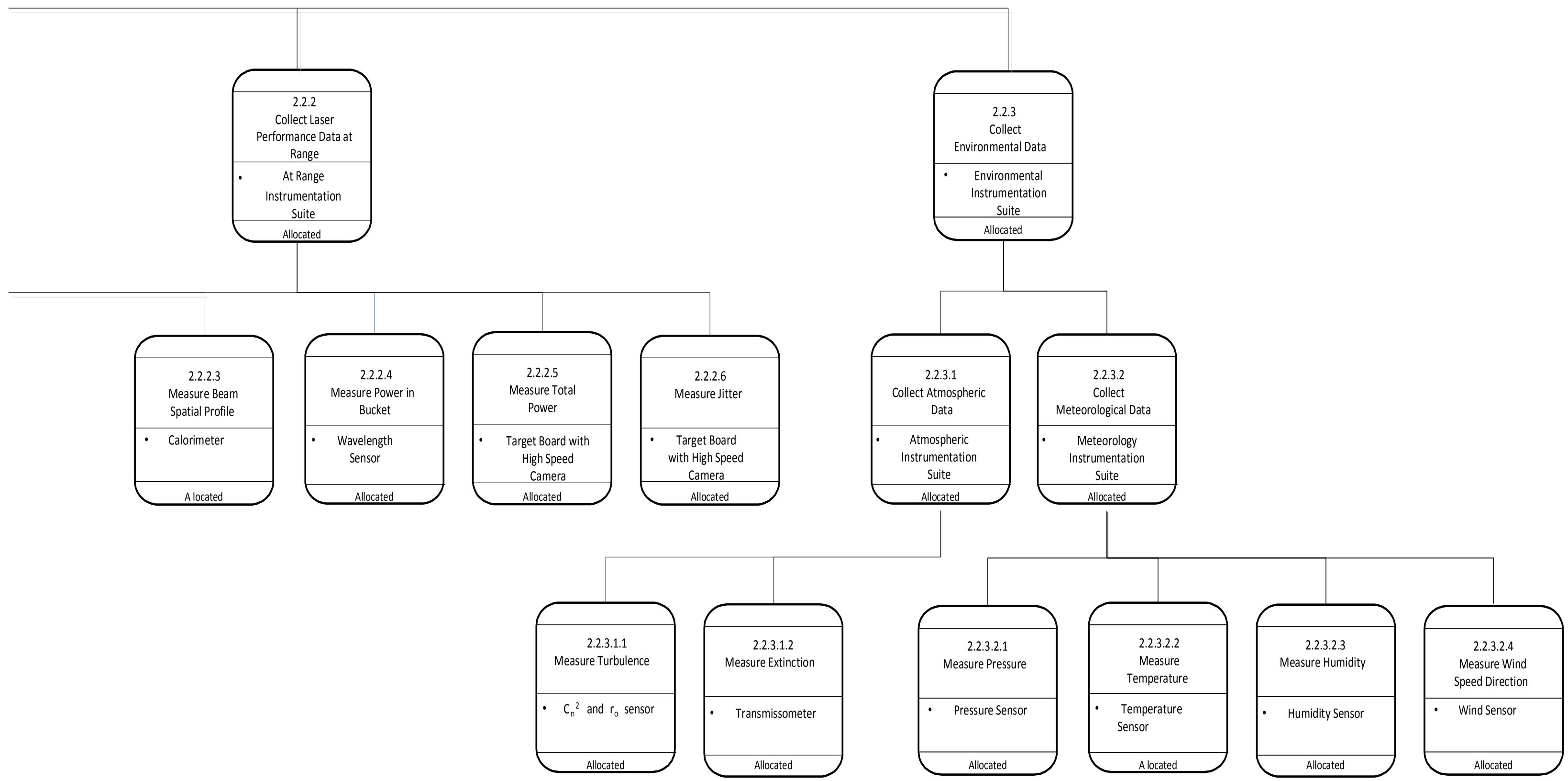
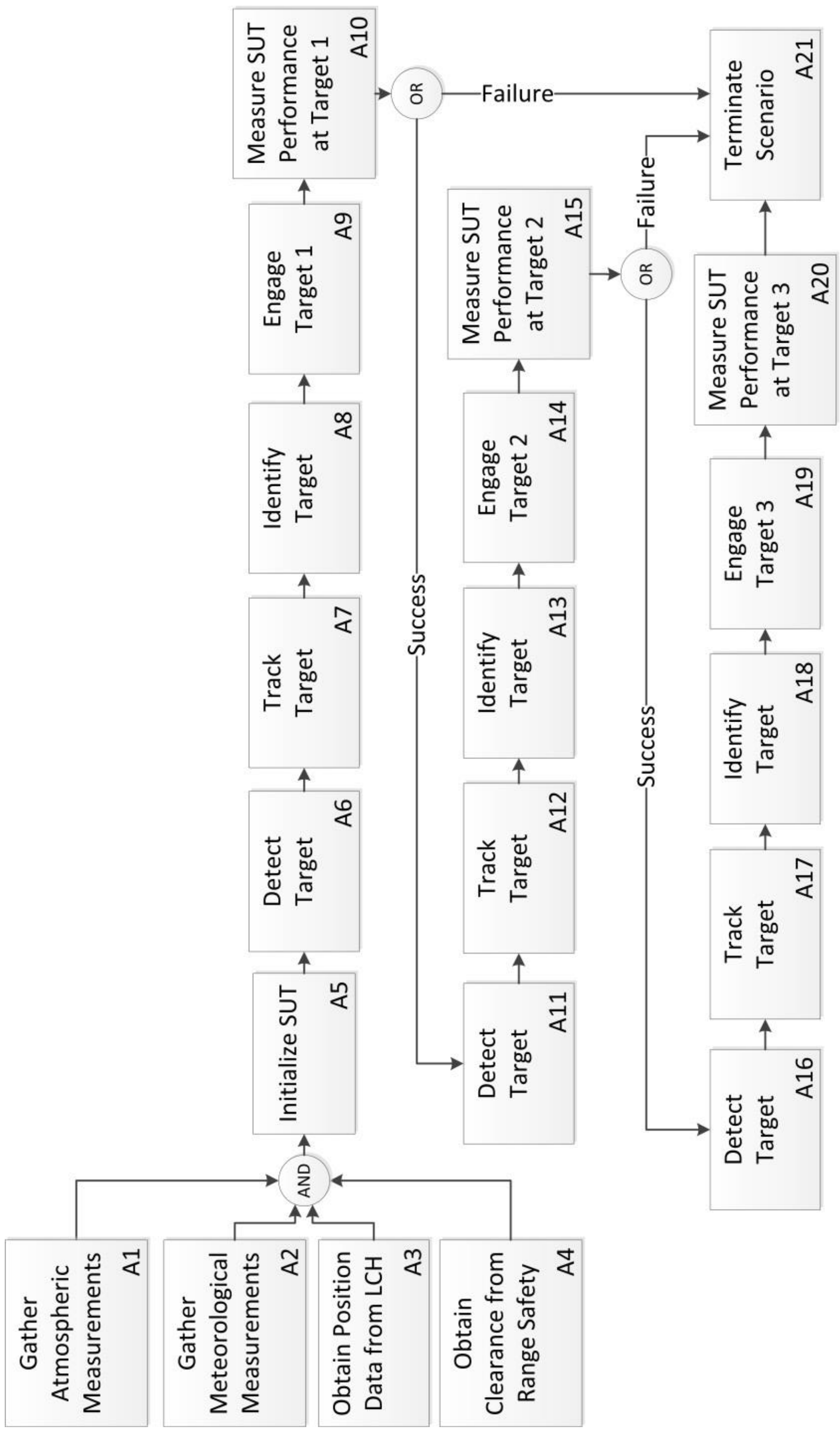
APPENDIX A – ARCHITECTURE SAMPLE




2.2.2
Collect Laser Performance Data at Range
At Range Instrumentation Suite
Allocated
2.2.3
Collect Environmental Data
Environmental Instrumentation Suite
Allocated
2.2.2.3
Measure Beam Spatial Profile
Calorimeter
A located
2.2.2.4
Measure Power in Bucket
Wavelength Sensor
Allocated
2.2.2.5
Measure Total Power
Target Board with High Speed Camera
Allocated
2.2.2.6
Measure Jitter
Target Board with High Speed Camera
Allocated
2.2.3.1
Collect Atmospheric Data
Atmospheric Instrumentation Suite
Allocated
2.2.3.2
Collect Meteorological Data
Meteorology Instrumentation Suite
Allocated
2.2.3.1.1
Measure Turbulence
C_n^2 and r_o sensor
Allocated
2.2.3.1.2
Measure Extinction
Transmissometer
Allocated
2.2.3.2.1
Measure Pressure
Pressure Sensor
Allocated
2.2.3.2.2
Measure Temperature
Temperature Sensor
A located
2.2.3.2.3
Measure Humidity
Humidity Sensor
Allocated
2.2.3.2.4
Measure Wind Speed Direction
Wind Sensor
Allocated

APPENDIX B – FUNCTIONAL FLOW BLOCK DIAGRAM

During the conceptual design phase, it is important to begin the development of a high level functional analysis of the system. As the details of a test scenario are being established, it is critical to analyze the function of each system at a lower level. Laying out a functional flow block diagram is useful in performing a functional analysis to visualize the interaction between each of these systems and determine if all the steps of a process lead to an achievable scenario. As an initial validation, the most complex and demanding scenario could be analyzed at a high level to determine if other simpler scenarios are also possible. For a laser test bed, one of the most taxing test scenarios would be a sea-based engagement involving multiple airborne targets. The functional flow block diagram depicts the high level functions of the test bed for such a scenario.


Gather Atmospheric Measurements A1
Gather Meteorological Measurements A2
Obtain Position Data from LCH A3
Obtain Clearance from Range Safety A4
AND
Initialize SUT A5
Detect Target A6
Track Target A7
Identify Target A8
Engage Target 1 A9
Measure SUT Performance at Target 1 A10
OR
Failure
Success
Detect Target A11
Track Target A12
Identify Target A13
Engage Target 2 A14
Measure SUT Performance at Target 2 A15
OR
Failure
Success
Detect Target A16
Track Target A17
Identify Target A18
Engage Target 3 A19
Measure SUT Performance at Target 3 A20
Terminate Scenario A21

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